STEEL RAILS

THEIR HISTORY, PROPERTIES, STRENGTH
AND MANUFACTURE

WITH NOTES ON THE

PRINCIPLES OF ROLLING STOCK AND TRACK DESIGN

BY

WILLIAM H. SELLEW

PRINCIPAL ASSISTANT ENGINEER, MICHIGAN CENTRAL RAILROAD

361 ILLUSTRATIONS–33 FOLDING PLATES

NEW YORK

D. VAN NOSTRAND COMPANY

TWENTY-FIVE PARK PLACE

LONDON

CONSTABLE & COMPANY, LTD.

1913

Stanhope Press
F. H. GILSON COMPANY
BOSTON, U.S.A.

PREFACE

In this work the author has endeavored to systematize the knowledge in existence upon the subject, and to present in a concise yet clear form the most important features of the problem.

The first chapter treats of the development of the present design of section with a comparison of the American rails with those in use on English Railways and on the Continent.

In chapters two to five, inclusive, the external forces acting on the rail and the corresponding stresses they produce in the rail are discussed. The necessity and desire for information on this subject are widespread. While a considerable amount of general information is to be found scattered through the technical press and in the proceedings of the various Railway Associations and Engineering Societies, yet very little has been published dealing broadly with the principles of design of the rail in reference to the rolling stock and track structure.

In recent years much thought has been given to the manufacture of rail steel, and investigators, it would seem, have turned their attention more to an examination of the various defects found in the process of manufacture than to the study of the duty of the rail.

Quite early the question of the intensity of pressure existing between the wheel and the rail began to receive attention, but it was not until later that the bending stresses in the rail were investigated. Purely theoretical contributions to the latter subject were made by Zimmerman in 1888. The first practical investigations of the bending stress in the rail were apparently those made by the United States Government in 1894 by measuring the strains in the rail under the static load of the locomotive wheels. These were followed by Dr. P. H. Dudley's stremmatograph experiments for measuring the effect of dynamic loads. In the time elapsed since the publication of these investigations hardly anything has been done to further elucidate this problem.

The sixth chapter deals with the detail of manufacture of the rail. The different stages in the process are described and the influence of each upon the finished product is pointed out. It would be outside the limits of the present

work to attempt a complete treatise on the manufacture of steel; the discussion concerns itself, therefore, chiefly with the practical results obtained rather than with theoretical considerations.

In the last chapter are given Rail Specifications representing the best modern practice in this country and abroad. The forms recommended by the American Railway Engineering Association for reports and record of the rail are added for the sake of completeness in an appendix.

The greater part of the bibliography of rail specifications given in article 39 was prepared for the present work by the Secretary of the American Society of Civil Engineers. The other shorter bibliographies appended to the discussions of several of the subjects were compiled by Mr. McClelland, Technology Librarian of the Carnegie Library of Pittsburgh. These, which are intended to supplement certain parts of the text, are not exhaustive but are thought to contain most of the important articles since 1906 which come within their scope. A bibliography for the years 1870–1906 with chronological arrangement appears in the Transactions of the American Institute of Mining Engineers, Vol. 37, pp. 617–627.

A comprehensive bibliography of steel manufacture would be so extensive as to be unwieldy. Exhaustive bibliographies on this subject appear in the various volumes of the Journal of the Iron and Steel Institute, and a good selective bibliography of iron and steel manufacture appears in Bradley Stoughton's "Metallurgy of Iron and Steel." For the average reader who desires a more detailed discussion of the processes of manufacture of steel, Harbord's and Hall's excellent volume on the Metallurgy of Steel will generally be found sufficient. It is believed that these references, together with the information contained in the footnotes throughout the book, will permit a thorough examination of any of the subjects to be made.

The work is essentially a compilation. The author has, however, in every case endeavored to give credit where anything has been drawn from an outside source, and if he has been remiss in this respect it has been unintentional. In the discussion of the granular structure of steel he has been much indebted to the work of Mr. J. W. Mellor, from whose writings a considerable part of article 25 has been taken.

The publications of the "Railway Age Gazette" have been freely quoted from and the author wishes to express his appreciation of the courteous permission given for the use of this material and for the many quotations taken from other sources, especially those from articles which have appeared in the Proceedings of the American Railway Engineering Association.

He has much pleasure in expressing his indebtedness to the following gentlemen who have given assistance in revising manuscript or proofs of the parts named: Professor Gaetano Lanza, mathematical discussions of Chapters II to V inclusive; Dr. A. B. Pierce, checking the author's calculations in these chapters; Professor W. F. M. Goss, wheel pressures; Dr. Hermann von Schrenk, forestry; Professor W. K. Hatt, strength of tie timber; Dr. P. H. Dudley, stremmatograph tests; Mr. Harry D. Tiemann, impact; Mr. James E. Howard, repeated stress; Mr. A. L. Colby, manufacture and specifications; Mr. Robert W. Hunt, influence of detail of manufacture; Mr. Bradley Stoughton, effect of temperature during rolling, and Mr. E. T. Howson for examination of the proofs before finally going to press.

WILLIAM H. SELLEW.

DETROIT, MICHIGAN, July, 1912.

CONTENTS

LIST OF ILLUSTRATIONS

LIST OF PLATES

(All plates except V and VI are in the back of the book.)
(Plates V and VI are between pages 11 and 12.)

STEEL RAILS

CHAPTER I

DEVELOPMENT OF THE PRESENT SECTION

1. Early Sections

Apparently the use of steel rails was first resorted to on account of the poor quality of the iron rails of later manufacture. The wear of these iron rails took the form of crushing or lamination, which destroyed the running surface of the rail and rendered it unfit for use. An iron rail when manufactured, even in the best way, was little more than a bundle of rods; and the top slab under the heavy pounding of the locomotive had a tendency to spread sideways and become laminated. A steel rail, on the contrary, was rolled from a solid ingot and for that reason was much more durable.* Iron, in the matter of wear, exhibited very great irregularity, some rails showing signs of distress within a year or two of being laid down, while others afforded very satisfactory results.

† As an illustration of the latter assertion we can instance the experience on the main line of the North-Eastern Railway on certain sections of its system which may be taken as fair samples of the others. On that extending between Newcastle and Berwick, 66.8 miles of double way, the iron rails laid down in 1847 weighed 65 pounds per yard. Renewals commenced in 1855 and terminated in 1867. In these the weight was increased to 82 pounds per yard. The maximum duration of the 65-pound rails was 21 years and the minimum 8 years, the average being 12.8 years.

Mr. T. E. Harrison stated in 1867 that on 700 miles of permanent way of the North-Eastern Railway the average duration of the last complete set of rails was found to be about 15.5 years; and some which were laid down in 1834 were still in use.

* See The Manufacture and Wear of Rails by C. P. Sandberg, Minutes of Proceedings of the Institution of Civil Engineers, Vol. XXVII, Session 1867–8, and R. Price Williams's Paper "on the Maintenance of Permanent Way," ibid., Vol. XXV, p. 353.

† Principles of the Manufacture of Iron and Steel. I. Lowthian Bell. London, 1884.

The statements just submitted do not afford any proper criterion of the resisting powers of iron rails; for this can only be determined by the comparative weights of the engines, the amount of traffic, and the speed of the trains which have passed over them. According to Mr. R. Price Williams the average life of an iron rail, on the most heavily worked portions of the railways in the United Kingdom in the year 1878, may roundly be taken at about 17½ millions of tons.

There is nothing speculative in the assertion that iron rails made before the complete discontinuance of refining were, generally speaking, longer lived than those of later manufacture. No doubt in the later days of iron rails the permanent way was much more severely taxed than was formerly the case. The engines were more ponderous, the traffic was heavier, and the speed greater; but the experience of the North-Eastern Railway at all events indicates that rails of iron have occasionally been made to give very satisfactory results. Whether this be due to their having been made from refined metal, or whether indeed they were so made, we have unfortunately little means of proving. It is significant to note that during the twenty years preceding 1868 the price of iron rails had been gradually reduced to one-third of their original cost, and that this reduction was accompanied by the production of an inferior quality of rail.

* In America several of the railway companies began to use steel rails as far back as 1864. In that year the Chicago and Northwestern, the Philadelphia, Wilmington and Baltimore, and the Old Colony and Newport each laid portions of track with this metal. In the following year the Boston and Albany, the Boston and Providence, the Connecticut River Railroad, the Chicago, Rock Island and Pacific, and the Chicago and Alton each began the use of steel.

In September, 1869, a commission appointed to ascertain the extent to which steel rails had been tried in the United States ascertained that of fifty-seven railways then in operation, from which reports had been obtained, twenty-six had made use of steel in weights varying from 100 to 15,000 tons, the whole bulk reported as in use being 49,800 tons, equal to about 518 miles of tracks. This, however, did not by any means represent the total weight of steel rails laid throughout the States. The Commission already referred to was, indeed, particular in calling attention to the fact that on the first of January, 1870, there were at least 100,000 tons of steel rails laid down in America, and 10,000 tons of steel-headed rails besides. Of this quantity the largest bulk had been supplied by England, and almost entirely by the Atlas, Barrow and Dowlais Works, although several thousand tons had been contributed by three establishments in Germany.

* Steel — Its History, Manufacture, Properties, and Uses. J. S. Jeans. London, 1880.

In France the Paris, Lyons, and Mediterranean Railway Company decided, so early as 1867, to use only steel rails in relaying its permanent way on 860 kilometers of the Paris and Marseilles line, where more than 10,000 trains ran over each line of way yearly, at speeds which might reach 90 kilometers per hour.

In Austria steel rails were used as early as 1859 on the Northern Railway, connecting Vienna with Cracow. They were, however, of puddled steel, manufactured at the works of the Archduke Albrecht, at Carlshütte.

In 1861 one German mile (about 4.8 miles) of the main line was laid with steel rails by way of experiment. So much satisfaction was afforded by this trial that in 1865 it was resolved to reconstruct in steel the whole of the main-line permanent way, and by the close of that year thirty-five English miles had been laid. Previous to this, however, steel had been largely used in Austria for railway crossings — so much so, indeed, that at the close of 1864 there were, on the Northern line, 468 steel crossings as compared with 977 of iron.

In Russia several lots of steel rails were laid down previous to 1872, but the use of that metal cannot be said to have received a thorough impulse until, in the year named, the Russian Imperial Administration approved the construction with steel rails of the railways from Wjasma to Tula, Rjask, and Jetetz, and from Morschunsk to Siezran, a total length of 1200 kilometers. Previous to this time steel rails had been laid experimentally on the Nicolas Railway, where they were found to answer so well that in 1872 about 70,000 tons of steel rails were ordered for Russia, chiefly from Creusot.

In England, before the end of 1861, steel rails had been laid down on the Caledonian, Lancashire and Yorkshire, London, Brighton and South Coast, and Rhymney railways, as well as on the London and North-Western.

The first Bessemer steel rails made in America were rolled at the North Chicago Rolling Mill on the 24th of May, 1865, from hammered blooms made at the Wyandotte Rolling Mill from ingots of steel made at experimental Steel Works at Wyandotte, Mich. The experimental Steel Works at Wyandotte were erected in 1864, and were the first works started in the country for conducting the pneumatic or Bessemer process. The rolls upon which the blooms were rolled at the North Chicago Rolling Mill were those which had been in use for rolling iron rails, and, though the reduction was much too rapid for steel, the rails came out sound and well shaped. The first steel rails rolled in the United States upon order, in the way of regular business, were rolled by the Cambria Iron Company at Johnstown, Pa., in August, 1867,* from ingots made at the

* See paper on the Development of the American Rail and Track by J. Elfreth Watkins, Trans. Am. Soc. of Civil Engrs., April, 1890, Vol. XXII, p. 228.

works of the Pennsylvania Steel Company, at Harrisburg, Pa., rails were rolled by the Spuyten Duyvil Rolling Mill Company, at Spuyten Duyvil, N. Y., early in September of that year, from ingots made at the Bessemer Steel Works, at Troy, N. Y., then owned by Winslow and Griswold, but these were on experimental orders, and not regular ones from any railway company.*

Before, however, the American steel works had produced any Bessemer rails, or, indeed, before any such works had been executed in this country, the Pennsylvania Railway Company had imported from England a lot of about 150 tons. This was towards the close of the year 1863. Some little delay took place in slotting the rails to receive the track fastenings; they were not laid down until the early part of 1866, when they were placed on sidings in the yards at Altoona and Pittsburg, where they would be subjected to considerable use. As the rails appeared very brittle, it was not deemed expedient to place them in the main track where they would be passed over by trains at high rates of speed. None of them, however, were broken in the track, and as they exhibited little or no appearance of wear, other steel rails were ordered in 1867, of a quality combining more toughness with a sufficient degree of hardness, and experiments were continued to test the relative merits of the several descriptions of rail.

About 1864 the Erie Railway Company ordered from John Brown and Company, of Sheffield, England, 1000 tons of Bessemer steel rails at 25 £ per ton.

The American Commission of 1869 concluded, as the result of comparing reports obtained from twenty-six railways then using steel rails: (1) That extremes of temperature do not injuriously affect steel rails. The Grand Trunk Railway reports them as not injured by a temperature of 30 degrees below zero of Fahrenheit, and no other road appears to find them unable to stand a cold winter. (2) That the durability of steel rails far exceeds that of the best iron rails. The Erie Railway reports their steel rails as having outworn thirteen sets of iron rails, and as showing scarcely any sign of wear. The Philadelphia, Wilmington and Baltimore reports them as having outworn seventeen iron rails, and as showing little wear. The Chicago and Northwestern say that steel rails have outworn fifteen iron rails, and show no perceptible wear.

In 1874 a small committee of American experts† conducted a very careful and elaborate inquiry into the form, endurance, and manufacture of rails. In

* Private communication from Mr. Robt. W. Hunt.

† Appointed January 8, 1873, by the American Society of Civil Engineers, to determine "the best form of standard rail sections of the United States; the proportion which the weight of rails should bear to the maximum loads carried on a single pair of wheels of locomotives or cars; the best methods of manufacturing and testing rails; the endurance, or, as it is called, the 'life' of rails; the causes of the breaking of rails and the most effective way of preventing it, and the experience of railways in America

speaking of the comparative value of steel and iron rails this committee stated, that "while steel rails as we get them are tolerably uniform in quality, iron varies so much that no comparison can be made except of particular qualities or of averages of qualities widely different. We can as yet do little more than give the results of our own experience. In so doing we shall not only compare steel and iron, but also the effects of some different circumstances on the duration of both. It seems probable that the best iron, if homogeneous and the head of uniform hardness, so as to wear off evenly like steel, would, with machinery of moderate weight, wear a third or even half as long as steel. The chairman has found that his 62-pound iron rail, after carrying about 14,000,000 tons gross load, has worn off only about 25 per cent more than the steel rails on the same track and under the same circumstances. Probably it will not wear so well when the top crust is worn through. But owing to want of homogeneousness and uniformity the iron scales, splinters, laminates, or somehow disintegrates or mashes in spots before it wears out."

Ashbel Welsh, the chairman of this committee, subsequently presented a final report, giving particulars of the behavior of the steel rails, 53 pounds per yard. Believing that a very thin stem and a very thin base would possess sufficient strength, he designed a pattern in which as much metal as possible should be placed in the head, and as little as possible anywhere else. The height was 4 inches, the width of base 4 inches, the head fully $2\frac{3}{8}$ inches wide and $1\frac{1}{4}$ inches deep; radius of sectional curvature of the head 12 inches, stem $\frac{7}{16}$ inch thick, base $\frac{3}{16}$ inch thick at the edges; angle of base and of under sides of head 14 degrees, length of rails 30 feet, weight 53 pounds per yard.

The rails were rolled by John Brown and Company, and were laid in 1867 and 1868 at places exposed to very heavy traffic, on the railway between Philadelphia and New York, where iron rails had lasted only four months. In straight portions of the line, after having carried a gross weight of about 50,000,000 tons, mostly at high speeds, the heads had been worn down $\frac{1}{4}$ inch, having lost in weight about 6 pounds per yard. In some sharp curves the sides of the heads were so much worn that the rails were taken up in June, 1876.

The early steel rails were naturally made to the existing iron pattern. These were generally pear-headed in order to prevent the side of the head from breaking down, and were therefore not adapted to fishing. In 1866, as we have seen, Mr. Ashbel Welsh designed a section differing but slightly from the

in the use of steel rails." See paper on the Form, Weight, Manufacture and Life of Rails. A Report by Ashbel Welsh, C. E.; M. N. Forney, M. E.; O. Chanute, C. E.; and I. M. St. John, C. E. Trans. Am. Soc. of Civil Engrs., Vol. III, p. 87.

modern rail,* and in 1874 Mr. Chanute, chief engineer of the Erie Railway, investigated to determine the proper contour of the head by observing the contour of the rails worn down by the action of the wheels. The width and shape of the head having been provided for, the rail was considered as a beam, and as much metal as possible was taken from the web and flange to deepen it.

With the older sections the connections at the joints were very unsatisfactory, the design preventing the fishplate from supporting the head. If the plate could bear against horizontal surfaces, it would not be forced out laterally by the loads, but the rail could not be properly filled by rolling and the play would rapidly increase and could not be taken up. Mr. Chanute experimented to determine the correct angle of the under side of the head to hold the fishplate and found that with an angle above 15 degrees the plate was loosened by stretching of the bolts. This relieved the pressure and friction of the plate against the nuts and allowed them to turn. He therefore adopted the angle of 15 degrees under the head, and to avoid unnecessary metal in the flange he made its angle 12 degrees.

The adoption of an improved section was very slow, and as late as 1881 119 patterns of steel rails of 27 different weights per yard were regularly manufactured, and 180 older patterns were still in use, making a total of nearly 300 different patterns. This great variety of sections in use required the mills to keep a large number of different rolls in stock, and finally to standardize the design of the rail the present A. S. C. E. section, shown in Plate I, was presented to the society on August 2, 1893. These sections met with favor, and were adopted by many railroads, so that in a few years about two-thirds of the output of the rail mills conformed to this design.

The gradual evolution of the present design of rail is shown in Plate II. The earlier rails show the pear shape of the old iron rails, followed by the rails where the section was more adapted to fishing and having a better distribution of the metal to afford a stiffer rail.

The question of cylindrical tires and flat top rails was one on which there existed for a long time a great deal of difference of opinion among railroad engineers. In the early days of railroading the wheels were generally coned to a ratio of 1 in 20, and after the organization of the Master Car Builders' Association this ratio was adopted as the standard. This particular ratio apparently grew out of

* Robert L. Stevens in 1830 designed a "T" section of iron rail for the Camden and Amboy Railroad, and is generally considered to have been the inventor of the flat-footed rail. See Trans. Am. Soc. of Civil Engrs., Vol. IV, p. 236, and ibid., Vol. XXII, pp. 209, 216.

the prevailing practice at the car wheel foundries, and not from any theoretical consideration of the relation of the wheel to a curve.

The agitation for the cylindrical wheel grew out of efforts to measure the area of contact between the wheel and the rail, to determine the intensity of pressure on the metal, and led the Master Car Builders' Association, in 1886, to change their standard wheel section and reduce the coning ratio from 1 in 20 to 1 in 38, which was about the last draft that would allow free withdrawal from the mold.

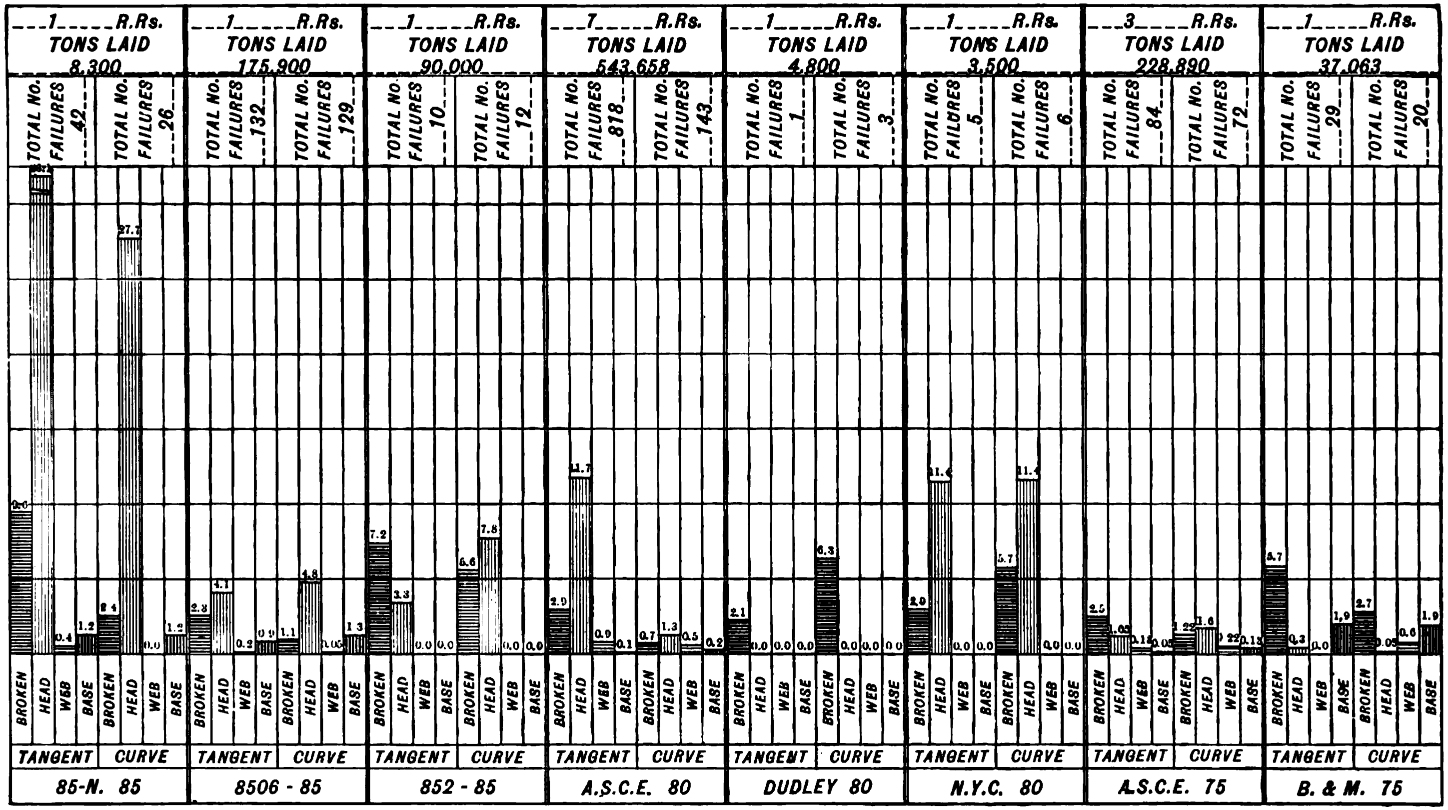
This section is shown on Plate III which also shows the cylindrical wheels considered by the Association at this period. The section thus recommended and adopted by the Association passed into general use on the railways of the country. It was noticed, however, that the change was followed by a large increase in the number of broken and sharp flanges, and after using the section for over twenty years it was restored to the former ratio of 1 in 20 as shown by the 1910 wheel given on the plate.

The rails of heavier section manufactured within the last few years are not giving the service that should be expected of them. The fault may lie in improper methods of manufacture or in the design of the rail itself, which, while suitable for the conditions existing nineteen years ago, may be unfitted for the heavy wheel loads of to-day.

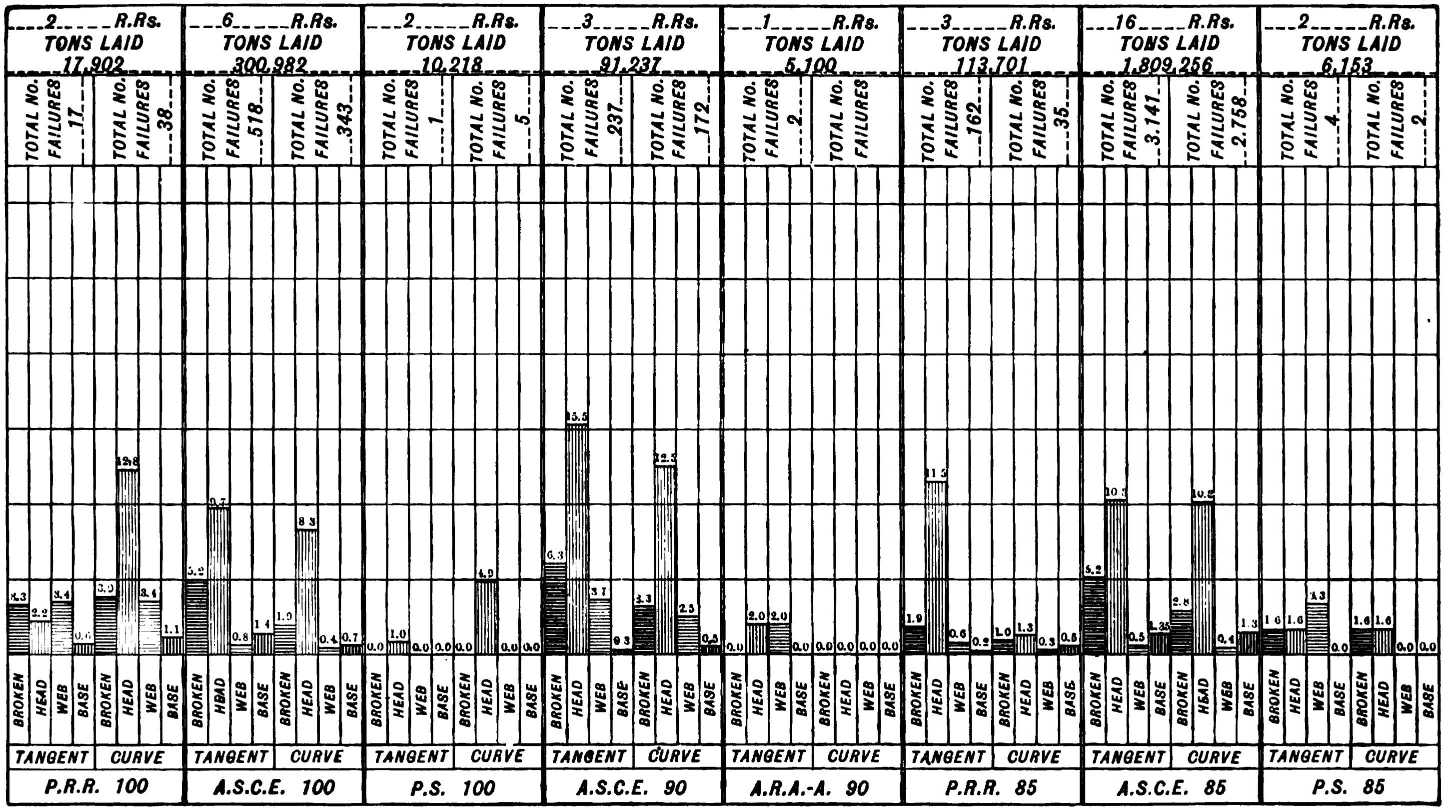
It has been claimed that the old committee of the American Society of Civil Engineers did not properly appreciate the importance of low finishing temperature in designing their rails, and that the sections recommended in its report in 1893 do not permit of a low enough finishing temperature in rolling owing to the wide, thin flanges.

As a matter of fact this was one of the points which received most careful consideration, not only by discussion between the members of the committee, but also in consultation with rail manufacturers. But a peculiarity of the situation comes from the fact, that at that time, what we now consider sections of necessary weight were then not in general use. The committee was instructed to devise sections from 100 pounds per yard down, decreasing by 5 pounds, but 80-pound sections were then regarded as the heaviest likely to be extensively used. Only one railroad at that time had heavier sections, and that was the Philadelphia and Reading, which had a few 90-pound rails in use. The New York Central had put in 80-pound rails, and perhaps they had a few heavier ones, but their standard was 80-pound. The Delaware and Hudson had adopted the 80-pound rail, also the Michigan Central.

The question was to devise a section which the committee considered a good one and which could be easily rolled. Unfortunately the sections be-



1 R.Rs. TONS LAID 8,300
TOTAL NO. FAILURES 42
TOTAL NO. FAILURES 26
1 R.Rs. TONS LAID 175,900
TOTAL NO. FAILURES 132
TOTAL NO. FAILURES 129
1 R.Rs. TONS LAID 90,000
TOTAL NO. FAILURES 10
TOTAL NO. FAILURES 12
7 R.Rs. TONS LAID 543,658
TOTAL NO. FAILURES 818
TOTAL NO. FAILURES 143
1 R.Rs. TONS LAID 4,800
TOTAL NO. FAILURES 1
TOTAL NO. FAILURES 3
1 R.Rs. TONS LAID 3,500
TOTAL NO. FAILURES 5
TOTAL NO. FAILURES 6
3 R.Rs. TONS LAID 228,890
TOTAL NO. FAILURES 84
TOTAL NO. FAILURES 72
1 R.Rs. TONS LAID 37,063
TOTAL NO. FAILURES 29
TOTAL NO. FAILURES 20
BROKEN HEAD WEB BASE
TANGENT CURVE
85-N. 85
8506 - 85
852 - 85
A.S.C.E. 80
DUDLEY 80
N.Y.C. 80
A.S.C.E. 75
B. & M. 75



LEGEND

P.R.R.—Pennsylvania R.R.
A.S.C.E.—Amer. Society of Civil Eng'rs.
P.S.—Pennsylvania System (New 1908)
A.R.A-A:Amer. Ry. Association. "Type "A"
85 N—Chicago, Burlington & Quincy R.R.
8.506—Chicago, Burlington & Quincy R.R.
852— " " " " "
Dudley—P.H. Dudley
N.Y.C.—New York Central R.R.
B.& M.—Boston & Maine. "

Fig. 1.—Comparison of Rail Failures between Different Sections of Bessemer Steel Rails, from Oct. 31, 1908, to April 30, 1909. Figures on the diagram show number of failures per 10,000 tons laid. (Am. Ry. Eng. Assn.)

yond 80 pounds were matters of compromise, and as they progressed arithmetically less satisfactory results were obtained as the weight increased.

It has been the invariable experience in changing from a light to a heavy section, in any class of rolled steel, that difficulties have been met and modifications have been made in the methods of rolling, in order to get as good structure in the heavier sections as was formerly obtained in the lighter sections. In ordinary sections other than rails it was a comparatively easy matter to overcome the trouble and get a good structure; but the thin flange of the rail, and the higher carbons called for in the heavier sections, further complicated matters.

The greatest need at this time is for reliable statistical information taken from properly kept records. The Committee on Rail of the American Railway Engineering Association have been engaged for several years in collecting statistics of defective rails on American roads. The classification adopted by the committee is as follows:

1. Broken Rail.
2. Damaged.
3. Flow of Metal.
4. Crushed Head.
5. Split Head.
6. Split Web.
7. Broken Base.

It is the intention of the classification that all rails which broke in service, or which have a straight crack working from top to bottom or from bottom to top, which would very quickly result in a broken rail, should be classified as "broken rails," regardless of internal defects. All of the other defective rails which are removed, not being "broken" or damaged on account of wrecks, broken wheels or similar causes, are to be classified under one of the other heads, from 3 to 7, both inclusive.

Fig. 1 shows a comparison of rail failures between different sections. (See Plates I, IV, VII and IX for description of sections.) The most striking characteristic of the diagram is the comparatively large number of head failures of 85 N, 85, both on tangent, 36.1 failures per 10,000 tons, and on curve 27.7 failures per 10,000 tons laid. The legend on the diagram explains that this is a Chicago, Burlington and Quincy section. It can hardly be said that the carbon is excessively high, although pretty high, unless it is badly segregated, the chemical constituents being:

Carbon	.48 to .58
Phosphorus	.10
Manganese	.80 to 1.10
Silicon	.20

Section 852, 85-pound, also a Chicago, Burlington and Quincy section, has the same composition, but the failures are not so numerous.

Carbon	.58
Phosphorus	.10
Manganese	.80 to 1.10
Silicon	.20

The next most numerous head failures are in the A. S. C. E. 90-pound on tangent, 15½ failures per 10,000 tons, and on curve 12½ failures per 10,000 tons laid. The P. R. R. 100-pound head failures on curve are 12.8 per 10,000 tons laid, while the head failures on tangent are small, and the head failures of the New York Central 80-pound are about as large, both on tangent and curve, 11.4 per 10,000 tons laid. The A. S. C. E. 80-pound on tangent, the P. R. R. 85-pound on tangent, and the A. S. C. E. 85-pound on tangent and curve have had the same number of head failures as the New York Central 80-pound. The A. S. C. E. 100-pound on tangent and curve comes next, and then 852, 85-pound on curve, while the rest were all less than 5 failures per 10,000 tons laid.

The breakages are most numerous in 85 N, 85-pound on tangent, 9.6 per 10,000 tons laid, and next of 852, 85-pound on tangent, with the A. S. C. E. 90-pound on tangent and the Dudley 80-pound on curve, both the same, following closely. Next comes the New York Central 80-pound and 852 85-pound on curve and the Boston and Maine 75-pound on tangent, all the same, and then A. S. C. E. 100 and 85-pound on tangent. The breakages of the others are less than 4 per 10,000 tons laid.

It will be observed that the breakages of so-called stiff sections are more numerous than those of the lower sections with the heavier head. The carbon is generally higher in the C. B. & Q. sections than in the A. S. C. E. and P. R. R. sections. The web and base failures are less than 4 per 10,000 tons laid.

Plates V and VI present photographs of typical rail failures collected by the committee.

Nearly nine million of tons of Bessemer steel rails, from seven different mills and varying in weight from 100 pounds to 75 pounds, were reported in the tracks of the American railroads on October 31, 1910. This corresponded to 21,503,803 rails, and for the twelve-month period from October 31, 1909,

11A

1. Broken Rails.

3. Flow of Metal.

4. Crushed Head.

PLATE V. — Examples of Defective Rails; Broken Rails, Flow of Metal and Crushed Head. (Am. Ry. Eng. Ass.)

5. Split Head.

11c

6. Split Web.

7. Broken Base.

PLATE VI. — Examples of Defective Rails; Split Head, Split Web and Broken Base.
(Am. Ry. Eng. Ass.)

11D

to October 31, 1910, there were 30,086 failures or one defective rail for every 714 rails laid in the track.

It will be interesting to turn to the conditions of twenty years ago. The following table * shows the rail failures on one of the American railways during the years 1884 to 1888 inclusive.

In track, June 1, 1884	121,685 tons
In track, January 1, 1889	162,526 tons
Removed from track, 1884 to 1888 inclusive, on account of:	
Broken	1,293¼ tons
Bruised	1,435¾ tons
Split	1,353¾ tons
Worn out	28¾ tons
No fault	35½ tons
Total	4,147 tons

The record is deceptive in some respects without an explanation. Many of the breaks in the older rails were caused by punching bolt holes. The record of the bruised or battered rails, which constituted the largest item, would have been still greater, except for the fact that long pieces of track laid with soft or so-called "pewter" rails showed up in such bad shape that they were taken up and the rails sent to branches or used in sidings after having been in use only a few months on the main line.

The road received the last of these soft rails in 1884, and the record given below of the rails received in the following four years is very good. All of the rails purchased in this period weighed 65 pounds per yard, but after 1888 an 80-pound section was adopted as standard. It will be observed that there were no failures from bruising in the harder rails received after 1884.

Year Rolled.	1885	1886	1887	1888	Total.
Total number of rails received during year	23,208	29,171	41,678	30,366	124,423
Rails removed to April 1st, 1889. Account:					
Broken	39	5	43	4	91
Bruised	0	0	0	0	0
Split	13	12	16	1	42
No fault	0	0	2	2	4
Total	52	17	61	7	137
Number of rails in the track, April 1st, 1889	23,156	29,154	41,617	30,359	124,286
Defective rails:					
for entire period	0.22%	0.06%	0.14%	0.02%	
per year	0.06%	0.02%	0.07%	0.02%	
per year, per 10,000 tons laid	21	7	24	7	

* Cylindrical Wheels and Flat Topped Rails for Railways, D. J. Whittemore, Trans. Am. Soc. of Civil Engrs., Vol. XXI, 1889, pp. 185, 186.

There appears to have been a critical period occurring about every twenty years in the history of the rail. When the iron rails replaced the old strap irons and other early forms of track construction, they proved very satisfactory for the light wheel loads of the day. The wheel loads, however, were rapidly increased and soon demanded heavier sections and a metal better able to resist wear at the running surface of the rail. It was claimed that the metal in the larger sections was poorer than that found in the early iron rails. Various experiments were tried with rails having steel heads, but it was not until the invention of the Bessemer process for making steel, which enabled a stronger and more uniform rail to be made, that the difficulty was successfully met.

The use of steel in place of iron for rails commenced about 1865 and enabled heavier wheel loads to be used with safety. The early steel rails were generally made of mild steel which, while suitable for the loads of the early seventies, was found to be too soft for the heavier equipment of the next decade. The situation was unfortunately complicated by the experiments on the Pennsylvania Railroad which showed, or seemed to show, that low carbon steel rails were to be preferred to those made from steel of greater hardness, and for several years following 1881 the rails were made too soft, and, while there was not a return to the serious difficulties of the time of the iron rails, the condition of affairs was far from satisfactory.

Relief was found by increasing the hardening constituents in the steel, but with the constant increase in the weight of engines and cars, as well as the greater density of traffic incident upon the growth of the industrial resources of the country, the situation again reached an acute stage about 1905 when the failures of rails became so numerous as to cause the gravest concern on the part of those in charge of the operation of the roads.

The failures as before were principally a question of wear rather than of breakage. It appeared that each increase in section produced a rail that wore out more rapidly than the lighter section which preceded it. This condition was further accented by the form of the American Society of Civil Engineers' sections with their thin bases, which turned black in the rolls while the heads were still hot, and the fact that the larger sections took more time to cool and so underwent a partial annealing, making the metal more readily abraded.

Three principal reasons were advanced as to the probable cause of the poor service of these latter rails. It was claimed that the wheel loads in use in this country were exceeding the limits of strength of the steel in the rail and, without resorting to extraordinary methods of manufacture and consequently greatly increased cost, the rails could not be made to carry the loads imposed

upon them with a proper degree of safety. The standard sections then in use were those of the American Society of Civil Engineers and this design of rail, in the heavier sections then demanded, was stated to be an impracticable one to roll.

The manufacturers of rails proposed these explanations as the real reason which accounted for the failures of the rails in service. The railways, on the other hand, while admitting that the metal of the rails would not stand the heavy wheel loads, claimed that this was due to the fact that the steel was of poorer quality than that obtainable in rails of earlier make, and that sufficient care was not being given to the details of manufacture in the various processes at the mills. The increase in the number of rail failures of the type designated as "crushed heads" and "split heads" the manufacturers claimed was caused by the metal breaking down under the excessive pressure of the heavy wheel loads, and the railways contended that they were due to some defect in the structure of the individual rails.

No one at all conversant with the situation will attempt to maintain that the subject is not a pressing one. The making of steel rails for use under high-speed passenger trains is something more than a mere commercial proposition. Both the producer and the consumer have great responsibilities in the matter, and neither can lay them aside nor shift them upon the other.

2. Present Sections

Realizing the importance of the question, the American Railway Association appointed a special committee on Standard Rail and Wheel Sections. This committee, through a subcommittee on which the manufacturers were represented, devoted a large amount of time and attention to the matter of sections and specifications for steel rails and presented a preliminary report to the association, October 1, 1907.

While the A. S. C. E. section was apparently well adapted for the light-weight rails of 65 pounds and 75 pounds in use when it was designed, the increase in weight on railway wheels (see Fig. 2) necessitated a heavier rail, and the manufacturers of rails claimed that it was difficult to make such rails of the A. S. C. E. section, due to the thin edge of the base.

Accompanying the report of the committee were two series of proposed standard rail sections: Series "A" designed to meet the requirements of those who advocate a rail with thin head and a high moment of inertia, and series "B" to meet the requirements of those who think that there should be a narrow, deep head, with the moment of inertia a secondary matter. These sections are shown in Plates VII and VIII.

The one known as Series "A" is characterized by a shallow head, wide base, thin flanges, and a greater height of section than Series "B." It is apparently advocated by those who think that more of the duty of the track should be borne by the rail and less by the other elements. It is obvious that the stronger the rail, as a beam or girder, the more the strains are distributed, and the less need, therefore, for exacting attention to the other features of track maintenance. Its advocates think that the distribution of metal between head, web, and foot, is such that the rolling difficulties, and especially the question of finishing temperatures, can be met with better success.

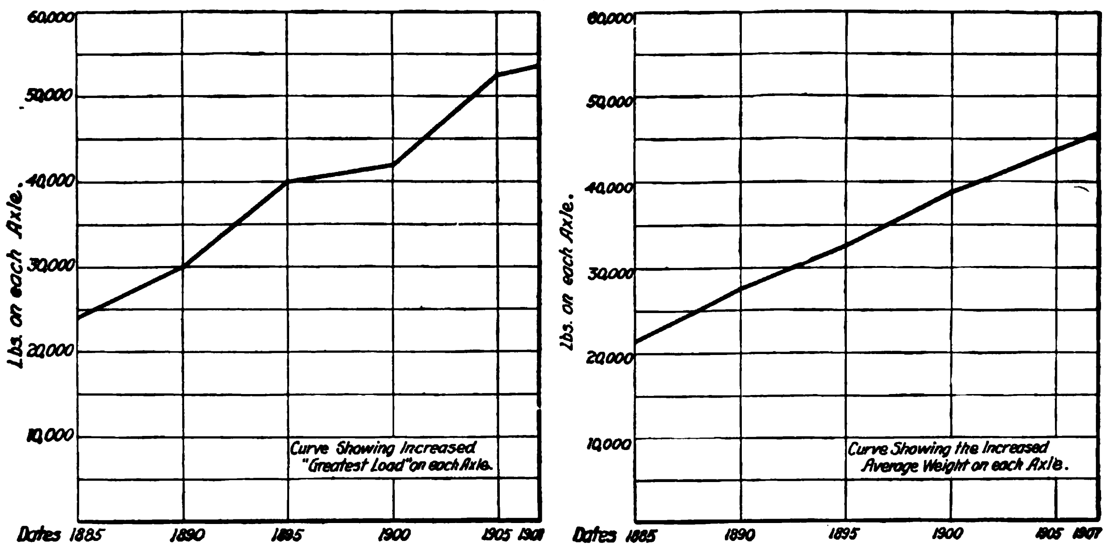


Fig. 2. — Increase in Axle Loads, 1885 to 1907. (Railway and Engineering Review — Wille.)

It is entirely problematic whether this section will prove the best of the two under consideration, and especially whether the transference of more of the duty to the rail will result in ultimate track economy. Those who oppose this section fear that the shallow head is an element of weakness. According to their view, with such steel as it is at present possible to get in rails, the pounding of the heavy traffic will lead to such crushing and splitting of the heads, owing to internal physical defects in the metal, that the section will prove a failure, especially on roads with heavy wheel loads and dense traffic.

Series "B" is modified to meet this latter view. The distribution of metal is believed, as in the "A" section, successfully to meet the manufacturers' criticism, the head and foot in the 100-pound rail having slightly over forty per cent each of the metal, and the web the balance. This section is weaker as a girder than the "A" section, and it would appear that for lighter rails the

section "A" should preferably be used to obtain the greatest stiffness. Where the wheel loads are sufficiently large to require the heavy head of the "B" section, the design of the rail should, however, approach more nearly the latter section, even at the expense of lack of stiffness which may be compensated for by strengthening the track structure or increasing the weight of rail used.

There is no good reason why the same characteristics of design should be carried out for an entire series. With the excessive loads borne by the heavier rails more attention must undoubtedly be given to the effect of the concentrated pressure at the point of contact of the wheel and the distribution of this force to the base of the rail. The bending stress while of equal importance can be reduced by strengthening the track structure as a whole. Hence under the most severe conditions a section should be used in which ample provision has been made for the former stresses and the question of the bending stress, while not lost sight of, becomes of secondary importance. As the section decreases in weight the importance of the stiffness of the rail increases, until in the lighter sections, supporting small wheel loads, a very much higher relative moment of inertia is to be desired than in the heavier rails of the same series.

The sections "A" and "B" have been proposed as "recommended practice" by the American Railway Association, and have been referred to the American Railway Engineering Association to study and accumulate data and make a report after the sections have been sufficiently tried in service to enable an opinion to be formed as to their respective merits.

The American Railway Association Committee, in its report of October 1, 1907, submitted a statement of cardinal principles which should govern the design of a series of rail sections, as follows:

(*a*) There should be such a distribution of metal between the head and the base as to insure the best control of temperature in the manufacture of the rail.

(*b*) The percentage of metal in the base of the rail should preferably be equal to or slightly greater than that in the head, and the extremities of the flanges should be sufficiently thick to permit the entire section to be rolled at low temperatures. The internal stresses and the extent of cold straightening will be reduced by this means to a minimum, and at the same time the texture of the section will be made approximately homogeneous.

(*c*) The sections should be so proportioned as to possess as great an amount of stiffness and strength as may be consistent with securing the best conditions of manufacture and the best service.

(*d*) The following limitations as to dimension details of the sections are considered advisable for the various weights per yard:

I. The width of base to be $\frac{1}{2}$ inch less than the height.

II. The fishing angles to be not less than 13 degrees and not greater than 15 degrees.

III. The thickness of the base to be greater than in the existing sections of corresponding weight.

IV. The thickness of the web to be no less than in the existing A. S. C. E. sections of corresponding weight.

V. A fixed percentage of distribution of metal in head, web, and base for the entire series of sections need not be adhered to, but each section in a series can be considered by itself.

VI. The radii of the under corner of head and top and bottom corners of base to be as small as practicable with the colder conditions of rolling.

VII. The radii of the fillets connecting the web with head and base to be as great as possible, for reinforcing purposes, consistent with securing the necessary area for bearing surface under the head for the top of the splice bar.

VIII. The sides of the head should be vertical, or nearly so.

IX. The radii of the top corners of the head should not be less than $\frac{3}{8}$ inch so long as the wheels continue under the present standard of the Master Car Builders' Association.

The principles (*a*), (*b*), and (*c*), above enumerated, appear to cover the proper design of T-rail sections. The (*d*) limitations as to dimension details should be approached tentatively rather than regarded as a cardinal principle.

Since October, 1907, a large tonnage has been rolled of rails substantially in accordance with the new sections, both series "A" and "B." It has been demonstrated that these sections can be finished in the mill at a lower temperature than the A. S. C. E. sections,* and therefore a finer grained and better wearing rail should be secured with the new section. However, great care must be exercised at the mills to see that rails are actually rolled at lower temperatures. The 90-pound series "A" is now used on a majority of the Western prairie roads, and the "B" section is used on the group of coal roads in Maryland and Virginia. On account of the heavier head found in the "B" section, it seems to be preferred by the crooked roads of the East, especially those in the

* This refers to the temperature of the head; no part of the new sections is finished as cold as the thin bases of the A. S. C. E. rails.

mountains of Pennsylvania, Virginia and Maryland; while on the prairie roads, where little curvature is found, the series " A " rail with the lighter head finds more general use.

On June 5, 1907, a joint committee of the Pennsylvania Railroad system — Mechanical and Civil Engineers east and west of Pittsburg — was appointed to study the rail question, and on September 20, 1907, their labors resulted in the designs for 85-pound and 100-pound rail sections shown in Plate IX.

It will be noted that the sides of the head are vertical in the 85-pound section and sloping in the 100-pound section. This difference is not intentional, but arises from the method of constructing the sections. The bearing surface underneath the head for supporting the shoulder of the splice bar was considered of great importance, and the committee was not warranted, in the light of past experience, in reducing this surface. This was therefore fixed at not less than the existing bearing surface.

As the same equipment is run over the 85-pound and 100-pound sections, there was no good reason why the width of the head on top should not be the same in each case, and, after studying the contour of the wheel tread, this width was fixed at $2\frac{1}{2}$ inches. The result was sloping sides in one case and vertical sides in the other.

This section, known as the "P. S." section, is a step farther away from the "A" section. It has a still heavier head, a narrower base, and thicker flanges than the "B" section. The radius of the web is smaller, thus producing more of a buttress where the head and web join. The experience of the Pennsylvania system seems to be that with their heavy wheel loads and dense traffic, and with the grade of steel that it is now possible to get in rails, more rails fail from crushing and disintegration of the head, apparently due to the pounding of the traffic, than from any other one cause, and accordingly in this section the maximum effort has been made to strengthen the rail in its weakest point. The distribution of the metal is satisfactory, and the strength of the rail as a girder or beam is practically the same as the "B" section.

In Europe a T-rail section is used. The Vignole rail used extensively abroad was invented in England in 1836 by Mr. Charles Vignoles. Plate X shows the type of Vignole rail used on the French Eastern Railway. It is their intention eventually to modify the section by decreasing the height of the head a little and increasing its width. The weight of the section is 45 kilos per meter or about 91 pounds per yard. The maximum axle load is about 40,000 pounds.

Plate X shows the rail used on the Paris, Lyon and Mediterranean, weighing 48 kilos per meter, or 96.7 pounds per yard. The maximum axle load on this road is, for passenger service, 38,000 pounds, and, for freight service, 35,000 pounds.

Plate XI illustrates types of German rails. The figures show that the corner radius of the head in all the rails is $\frac{9}{16}$ inch, as prescribed by the "Technical Conventions of the Union," which also recommends a width of head of at least $2\frac{1}{4}$ inches with a minimum radius of the top of the head of $7\frac{7}{8}$ inches. On the majority of the German rails the latter radius is from $7\frac{7}{8}$ to $8\frac{7}{8}$ inches. An inclination of $\frac{1}{20}$ is given to the rails, which is obtained by the use of wedge tie plates.

Plate X shows the Vignole rail recently used on the Egyptian State Railways, of 46 kilos, or 92.7 pounds.*

In England the idea seems to prevail that a T-rail track is undesirable, and a double-headed, or bull-headed, rail is generally used on the English railways. Plate XII shows the construction of the permanent way of the Midland Railway of England, and Plate XIII the permanent way of the London and North Western Railway of England. On the latter road the British standard bull-headed rail is used, as shown on Plate XIV. Plate XV shows the British Standard flat bottom rail.

For street railway work either a T-rail or grooved-rail section is employed. as illustrated on Plates XVI and XVII, which show the sections recommended by the American Electric Railway Engineering Association. This association has only taken up the study of girder and high T-rail sections, and the sections of tram rails given on Plate XVI, while representative of good practice, are not the standard sections of the association. Plate XVIII shows the British Standard tramway rails.

While the T-rail is generally recognized in this country as having superior merits for street railway purposes, it is necessary, however, on heavily traveled streets to use the grooved rail. The use of a number of different rail sections in street railway work is open to the same objections as are found in steam railway practice, and the tendency is toward the adoption of standard sections.

In determining the proper form for a rail, the subject should be considered from two points: First, and most important, the duty required. Second, and about equally important, the influence of detail of manufacture upon the character of the finished product. It is perfectly proper that all the stresses to

* This rail has been replaced by another weighing 95 lbs. per yard, according to British Standard sections, which was laid from the year 1911.

which it will be subject should be considered and calculated, but its ability to resist them will depend quite as much upon the character of the metal as upon the form of section.

In considering the duty, we have first to examine the external forces acting upon the rail, which consist of the pressure exerted by the wheel on the rail and the supporting forces represented by the ties. When these are known, the stress induced in the rail can be calculated for different sections.

CHAPTER II

PRESSURE OF THE WHEEL ON THE RAIL

3. Speeds of Modern Locomotives

The eight-wheel or American engine was formerly the favorite type for fast passenger service. The arrangement of this engine provides a four-wheel leading truck and four-coupled driving wheels and afforded ample starting capacity for the trains of moderate weight used at that time.

The Atlantic type is the result of the demand for large heating surface and grate area in combination with large driving wheels in an effort to meet conditions which could not be met successfully by the preceding American-type engine. The Atlantic-type engine combines a four-wheel leading truck and four-coupled driving wheels with trailing wheels.

The increase in the weight of the train due to heavier equipment and longer trains has resulted in the use of the Pacific locomotive with six-coupled wheels in place of the Atlantic type with four-coupled wheels. The latter engine is better suited to high-speed service than the former, but it cannot accelerate heavy trains to running speed nor maintain speed on grades as well as the Pacific. The internal friction of the Pacific engine is much greater than that of the Atlantic and it reaches its speed limit sooner, and in fact these powerful engines have not been able to show any material increase in the speed of our fast trains.

A train * was recently made up for test purposes which was intended to represent modern express equipment which could be hauled at high speed on level track. The six cars weighed 350 tons, and the Pacific locomotive 194 tons, total 544 tons. The Pacific locomotive, which was selected for its good record on that line, was not able to accelerate the train to more than a fraction above 60 miles per hour on a straight level track where atmospheric conditions were normal.

On several railways in the West it was for a time thought that it would be necessary to electrify the mountain divisions in order to attain speeds which would carry the large volume of traffic over the grades and avoid congestion and blockade. The Mallet locomotives have overcome this difficulty, and their

* Railway Age Gazette, January 28, 1910.

remarkable performance has for the time rendered the electric locomotive on mountain lines, where there are no long tunnels, unnecessary.

On account of the good results obtained by the use of the Mallet compound locomotives it will prove interesting to consider the question of adopting these machines for fast service. The principal advantage to be derived from the use of the Mallet type appears to lie in its ability to develop enormous force at the draw-bar, but it will be observed that these forces are only possible at comparatively low speeds.

At speed,* whatever the type may be, it is the boiler and not the adhesion that limits the output of power. The moment the speed is increased by any considerable amount, high draw-bar forces become impossible and the wheel arrangement peculiar to the Mallet type unnecessary. The assumption even of a moderate speed will permit wheel arrangements, now common, to absorb the full power of the largest boilers now considered practicable. For example, assume that a locomotive is used which is to have sufficient boiler capacity to permit 2000 h.p. to be developed in compound cylinders at all practicable speeds. Such a locomotive would require a boiler having in the neighborhood of 5000 feet of heating surface which, if fired with coal, would need to be supplied with 6000 or 7000 pounds per hour. The draw-bar force equivalent to 2000 h.p. for several different speeds is as follows:

At	1	mile	an hour,	the tractive force	will	be	750,000	lbs.
"	5	miles	"	"	"	"	150,000	"
"	$7\frac{1}{2}$	"	"	"	"	"	100,000	"
"	10	"	"	"	"	"	75,000	"
"	20	"	"	"	"	"	37,500	"
"	30	"	"	"	"	"	25,000	"
"	50	"	"	"	"	"	15,000	"

Assuming the driving axle of the proposed locomotive to carry a load of 50,000 pounds, and assuming the adhesion to be 25 per cent, each driving axle will serve to develop 12,500 pounds tractive force. A Mallet compound having eight axles would be capable of developing a maximum tractive force of 100,000 pounds, which force is equivalent to the development of 2000 h.p. in the cylinder at a speed of $7\frac{1}{2}$ miles per hour. At speeds lower than this the adhesion derived from eight axles will not permit the cylinders to develop this rated power, and for speeds higher than this the full adhesion of eight axles will not be necessary to the development of 2000 h.p.

* Railway Age Gazette, April 22, 1910.

Table I shows fast and unusual runs in the last three decades.* The foregoing table is severely condensed.† The time in every case is from the beginning to the end of the run, including stops. In speeds alone, for moderate distances, there has been little change since 1895. For example, the engines of the Atlantic City Railway make substantially the same time as was made over the same line ten years ago; but with the larger boilers and fireboxes now used, heavier trains are hauled without loss of speed. The Empire State Express of the New York Central, which for years was limited to four cars, now usually has five cars, and still makes its trip of 440 miles at the scheduled speed of

* Locomotive Dictionary, 1909 Edition, Chicago.

† *March* 1, 1901. — The record of 107.9 miles an hour is given by an officer of the road. The grade was descending, mostly at 30 feet per mile.

March 24, 1902. — This run was made on a descending grade, which for some of the way was as much as 32 feet per mile.

June 21, 1902. — This run is notable by reason of the rising grade. Altoona is 861½ feet higher than Harrisburg.

June 19, 1903. — This run was made without a stop, but there were two engines. The weight of the train was 1,008,000 pounds. There are a number of long ascending grades in the line.

August 8, 1903. — On this and the later run between the same places there were, of course, many changes of engines. The record gives no data concerning the sizes of the engines, but most or all of them were of the most powerful types made in the United States at that time.

June 9, 1904. — On this run engines were changed at Bristol. The dimensions given are those of the engine used on the second stage of the journey. A car was left at Bristol and the weight given is the average weight for the whole journey. The first engine had drivers 6 feet 8 inches in diameter, four-coupled; cylinders, 18 × 26 inches. The train making this run was the regular mail train scheduled to run regularly, without a stop, from Plymouth to London in 4 hours 25 minutes.

July 20, 1904. — This is the best record which has been made over this line. The run of June 19, 1906, was made with one more car.

1905. — Eighteen hours between New York and Chicago is the regular schedule time of one daily train each way over the New York Central lines, and one over the Pennsylvania, the latter being about 60 miles shorter. There is no published record of less time through, though on many occasions the trains of both roads have made up much lost time. The run of November 3, 1905, is an example of what has been done in such cases. In this run the number of cars was three, except over portions of the road where a dining car was added, making four.

October 23, 1905. — This run and that of May 5, 1906, were not undertaken with a view of making the highest possible speed, and each of the divisions over which these trains traveled has been traversed no doubt in shorter time; but these transcontinental records are notable for the long distances covered, even though the time be not the very highest of which the engines are capable. Both of these runs were made by special trains throughout, except that in the run of May, 1906, the run east of Buffalo was that of the regular Empire State Express.

June 19, 1906. — On this run a distance of 12 miles was traversed in 8 minutes (90 m.p.h.).

TABLE I.—FAST AND UNUSUAL RUNS, 1880–1906

(Locomotive Dictionary)

Month, Day, Year.	Railroad.	From	To	Distance.	Time.	Speed.	Cars. No.	Cars. Lbs.	Locomotives. Type.	Locomotives. Cylinders.	Locomotives. Diameter Drivers.	Locomotives. Weight on Drivers.	Locomotives. Weight of Engine.	Month, Day, Year.*
				Miles.	h. m. s.	Miles per Hour.					Inches.	Pounds.	Pounds.	
6-14-80	P. R. R.	Philadelphia	Jersey City	90	1 : 33 : 00	58.06	2		4-4-0					6-25-80
0- 0-80	Gt. N. (Eng.)	London	Grantham	105.5	1 : 51 : 00	66.5			4-4-2		96			8- 6-80
4-22-82	West Jersey	Camden	Cape May	81.5	1 : 23 : 30	58.63	3		4-4-0					4-28-82
7-12-83	S., B. & N. Y.	Syracuse	Binghamton	79	1 : 23 : 00	57.11	2		4-4-0					7-20-83
5- 9-84	P. & R.	New York Div.	M. P. 48	14	0 : 11 : 19	74.2	4		4-4-0					1- 6-84
5- 8-85	L. S. and N. Y. C.	Chicago	New York	964	22 : 45 : 00	42.38								5-15-85
7- 9-85	W. Shore	Alabama	Genesee Junction	36.3	0 : 30 : 00	72.60	3	153,660	4-4-0	18×24	68	62,500	94,500	8-28-85
6-17-86	C., B & Q	Princeton	Burlington	170	2 : 58 : 00	57.3			4-4-0					7- 2-86
7- 5-86	Wabash	Kansas City	Peru	563	13 : 45 : 00	41								7-16-86
8- 8-86	N. Y. C. & H. R.	Syracuse	Fairport	70.25	1 : 01 : 20	68.73	2		4-4-0					8-13-86
7-10-88	L. & N. W. Cal.	London	Edinboro	400	7 : 52 : 00	50.85								
8- 0-88	L. & N. W.	Crewe	Preston	51	0 : 50 : 00	61.20								8-24-88
8- 0-88	L. & N. W.	Preston	Carlisle	90	1 : 30 : 00	60								8-24-88
8-30-88	N. E. (Eng.)	York	Newcastle	80.5	1 : 18 : 00	62	7		4-2-2	18×24	84			12-14-88
8-31-88	Gt. N. (Eng.)	London	Edinboro	392.5	7 : 26 : 45	52.7						73,000		10- 5-88
4- 8-89	C. & N. W.	Chicago	Council Bluffs	490	12 : 30 : 00	39.2	4		4-4-0	18×24	63	59,850		
5-19-89	P., F. W. & C.	Ft. Wayne	Chicago	148.3	2 : 59 : 00	49.7	5		4-4-0	18×24	62		91,900	
5-26-89	Mich. Cent.	S. Bridge	Chicago	511	11 : 41 : 00	43.74								6- 6-90
3-10-90	P. & R.	Philadelphia	Jersey City	90	1 : 25 : 00	63.53	1							3-14-90
3-10-90	P. R. R.	Jersey City	Washington	226	4 : 18 : 00	52.56	3							3-14-90
3-10-90	P. R. R.	Washington	Jersey City	226	4 : 19 : 00	52.35	3							3-14-90
6-22-91	N. Y. C. & H. R.	New York	Buffalo	439.52	8 : 58 : 00	49.2	6	515,700	4-4-0	19×24			121,300	6-26-91
8- 0-91	Canadian Pac.	Vancouver	Brockville	2,792	76 : 31 : 00	36.49	3							9-18-91
9-14-91	N. Y. C. & H. R.	New York	East Buffalo	436.32	7 : 17 : 30	59.56			4-4-0	19×24				9-18-91
10-16-91	N. Ry. (France)	Paris	Calais	184	3 : 43 : 00	49.51	12	311,360		$\left\{\begin{matrix}13\frac{1}{4}\\20\frac{3}{4}\end{matrix}\right\}\times25$	84	67,200	96,320	
11-28-91	P. R. R.	Jersey City	Washington	227	4 : 11 : 00	54.22	3	250,000						12- 4-91
12-22-91	B. & O.	Philadelphia	Canton	91.6	1 : 41 : 00	54.41								1- 1-92
3-28-92	N. Y. C. & H. R.	Oneida	DeWitt	21.37	0 : 17 : 40	72.69			4-4-0	19×24	78	81,400	126,150	4- 7-93
11-18-92	Cent. N. J.	Fanwood		1	0 : 00 : 37	97.3	4	228,800		13, 22×24	78	88,400	123,800	11-25-92
11-18-92	P. & R.	Jenkintown	L'horne	5	0 : 03 : 25	87.8								
12- 0-92	L. & N. W	Crewe	Rugby	76	1 : 11 : 00	64.23	3							
5- 9-93	N. Y. C. & H. R.	Grimesville		1	0 : 00 : 35	102.8	4		4-4-0	19×24	86	84,000	124,000	6- 2-93
5-19-93	N. Y. C. & H. R.	Syracuse	East Buffalo	146	2 : 21 : 00	62.13			4-4-0	19×24	84	84,000	124,000	5-26-93
5-19-93	N. Y. C. & H. R.	Looneyville	Grimesville	5	0 : 03 : 00	100			4-4-0	19×24	84	84,000	124,000	5-26-93
5-28-93	N. Y. C. & H. R. / L. S. & M. S.	New York	Chicago	964	19 : 57 : 00	48.2				17×24	72	65,100	104,600	6- 2-93
8-28-93	P., C., C. & St. L.	Seymour	N. Tower	42	0 : 35 : 34	70.96	5		4-4-0		68			8-15-93
3-23-94	C. & N. W.	Council Bluffs	Chicago	488	12 : 52 : 00	41.1	8							4- 6-94
4-17-94	L. S. & M. S.	Cleveland	Erie	95.5	1 : 35 : 00	60.32			4-6-0					4-27-94
8-26-94	A. C. Line	Jacksonville	Washington	780.8	15 : 49 : 00	49.36								9-21-94

* Date reported in Railroad Gazette.

TABLE I (Continued). — FAST AND UNUSUAL RUNS, 1890-1906

Month, Day, Year.					Time.	Speed	Cars.		Locomotives.					Month, Day, Year.*
							No.	Lbs.	Type.	Cylinders.	Diameter Drivers.	Weight on Drivers.	Weight of Engine.	
					h. m. s.	Miles per Hour.					Inches.	Pounds.	Pounds.	
4-0-95	C., B. & Q.	Chicago	Galesburg	163	2.45:00	59 27	6		2-6-0	19×24	68	101,000	120,000	12-13-95
4-21-95	Camden & Atl.	Camden	Atlantic City	56 2	0.45.45	76 46	1		4-4-0		78	87,300	122,600	1 3-95
8-21-95	West Coast	London	Aberdeen	540	8.55:00	60 56								9-13-95
8-21-95	East Coast	London	Aberdeen	523	8:40.00	60 35								9-13-95
9-11-95	N. Y. C. & H. R.	New York	East Buffalo	436 32	6:51:56	63 54			4-4-0					9-27-95
9-24-95	N. Y. C. & H. R.	Albany	Syracuse	147 84	2:10:00	68 23	2		4-4-0	19×24		84,000	124,000	10-4-95
10-24-95	L. S. & M. S.	Erie	Buffalo	86	1·10:46	72 91			4-6-0	17×24	66	88,500	113,500	11-1-95
10-24-95	L. S. & M. S.	Chicago	Buffalo	510 1	8:01:07	63 61								11-1-95
10-24-95	P. R.R.	Jersey City	Philadelphia	89 6	1.33:21	57 6	6	546,657	4-4-0	18½×26		91,600	134,800	1-17-96
5-7-96	Mich. Cent.	Windsor	St. Thomas	111.2	1 43 05	64 73	3	230,050	4-6-0	19×24	68	96,300	123,500	
5-7-96	Mich. Cent.	St. Thomas	Fort Erie	118 2	1.47:15	66 13	3	230,050	4-6-0	19×24	68	96,300	123,500	
6-10-96	Atlantic City	Camden	Atlantic City	55.5	0·48 00	69 4	6		4-4-2	13, 22×26	84½	80,000	141,000	6-19-96
6-20-96	Atlantic City	Camden	Atlantic City	55 5	0.57.00	58 42	11	701,450	4-4-2	13, 22×26	84½	78,600	141,000	6-26-96
7-3-96	C., M. & St. P.	Forest Glen	Nat. Ave.	74	1·22·00	54 2	13	974,390	2-4-2	13, 22×26		71,600	140,700	1-22-97
11-21-96	S. & R.	Weldon	Shops	76 8	1.12.30	63 56	3		4-4-0	19×24	68	75,000	118,500	
2-15-97	C., B. & Q.	Chicago	Denver	1,025	18.53·00	54 27	1	72,000						2-26-97
3-11-97	Char. & Sav.	Cent. Junction	Ashley Junction	102	1.40 00	61 02			4-4-0	17×24	64	67,000	90,000	4-2-97
4-9-97	A. C. Line	Florence, S. C.	Rocky Mount	172 2	3·00·00	57 70	5		4-4-2	19×24	72	76,000	129,620	
4-21-97	Lehigh Valley	Alpine	Geneva Junction	44	0.33:00	80	4		4-4-0					
7-14-97	Atlantic City (P. & R.)	Camden	Atlantic City	55 5	0·46·30	71 60	5	320,300	4-4-2	13, 22×26	84	78,000	143,000	7-9-97
7-16-97	P., F. W. & C.	G. R. & I. Junction	Colehour	132 5	2.15·00	58 8	6	628,587	4-4-0	18×24	68	65,400	103,600	8-27-97
8-3-97	Union Pac.	Evanston	Omaha	955 2	23:55:00	39 93	3 }	264,755	4-4-0	19×24	69	81,000	119,600	10-22-97
8-3-97	Union Pac.	North Platte	Omaha	291.	5 35:00	52 1	3 }							
11-29-97	Union Pac.	Cheyenne	Council Bluffs	519 0	9:19:00	55 7								12-17-97
12-4-97	Union Pac.	Sidney	Omaha	414 2	7:12:00	57 5	3	276,000	4-6-0	20×24	69	103,000	131,200	12-17-97
							3	276,000	4-4-0	19×24	69	81,000	119,600	
							6	546,000	4-6-0	20×24	69	103,000	131,200	
2-18-98	Erie	Jersey City	Buffalo	423	7:30:00	56 4	3							2-18-98
8-20-98	Atlantic City	Camden	Atlantic City	55 5	0:46:45	71 2	7	437,700	4-4-2	13, 22×26	84	76,400 est.	143,000 est.	
1-2-99	Chic., B. & Q.	Omaha	Chicago	500 2	8:43:00	57 38								
4-23-99	Chic., B. & Q.	Clyde	Burlington	197 3	3·04:00	64 33	4	378,000	2-6-0	19×24	69	106,500	125,000	5-5-99
7-9-99	Del., L. & W.	Bath	East Buffalo	104	1·30:00	69 30								5-4-99
7-19-99	Vandalia	Clayton	Transfer	18	0.14 00	77	8		4-4-0	20×28	78	85,800		7-28-99
7-22-99	Atlantic City	Camden	Atlantic City	55 5	0 51·15	65	8							
7-31-99	W. J. & S. (Penn.)	Camden	Atlantic City	58 3	0:50.30	69 30	8			21, 5×26	80			8-11-99
10-7-99	Penn. Lines	Ft. Wayne	Chicago	148 3	2·50·00	52 30	6	688,857		19×24	68	112,550	138,000	11-10-99
10-14-99	Wabash	Tilton	Granite City	176 6	2:47.30	63 80	4	360,000	4-4-2	19×26	73	83,450	157,900	
11-22-99	L. S. & M. S.	Buffalo	Cleveland	183	3·25·00		8		4-6-0	20×28	80	133,000		12-1-99
3-27-00	A., T. & S. F.	Los Angeles	Chicago	2,236	58.00 00	38 55	2	148,900						4 13-00
4-30-00	C., B. & Q.	Burlington	Chicago	205 8	3·23 00	60 80	4		2-6-0	19×24	69	106,500	135,000	5-11-00

* Date reported in Railroad Gazette.

TABLE I (Concluded).—FAST AND UNUSUAL RUNS, 1880–1906

Month, Day, Year.	Railroad.	From	To	Distance.	Time.	Speed.	Cars, Weight.		Locomotives.					Month, Day, Year.*
							No.	Lbs.	Type.	Cylinders.	Diameter Drivers.	Weight on Drivers.	Weight of Engine.	
				Miles.	h. m. s.	Miles per Hour.					Inches.	Pounds.	Pounds.	
7- 9-00	N. Y. C. & H. R.	Rochester	Syracuse	80.7	1 : 25 : 00	56.70	7	639,400	4-4-0	19×24	84	84,000	124,000	
7- 4-00	Atlantic City	Camden	Atlantic City	55.5	0 : 44 : 15	75.20	4	364,000	4-4-2	15, 25×24	84	89,200	173,600	11- 2-00
8-16-00	Atlantic City	Camden	Atlantic City	55.5	0 : 44 : 15	75.20	5	456,000	4-4-2					
9-30-00	Penn. Lines	Ft. Wayne	Clarke Junction	126	2 : 38 : 00	47.90	9							10-26-00
12-21-00	C. B. & Q.	Omaha	Billings	892.6	16 : 23 : 00	54.40	1							1- 4-01
3- 1-01	Sav., F. & W.	M. P. 69	M. P. 74	4.8	0 : 02 : 40	107.90	3		4-6-0	19×28	73	108,000	146,000	3-22-01
9- 5-01	Mich. Cent.	Susp. Bridge	Windsor	229	3 : 40 : 00	62.45	5	430,000	4-4-2	21×26	79	95,000	176,000	11-22-01
2- 9-02	N. Y., N. H. & H.	Harlem River	Boston	228	4 : 12 : 00	54.30								2-21-02
3-24-02	Penn	Philadelphia	Jersey City	89.8	1 : 19 : 00	68.17	2							3-28-02
3-24-02	Burlington	Eckley	Wray	14.8	0 : 09 : 00	98.66	9		4-6-0	19×26	72		156,600	4-25-02
6-21-02	Penn	Harrisburg	Altoona	131.4	2 : 10 : 00	60.70	3	280,824	4-4-0	18½×26	80	93,100	134,500	7- 4-02
5-25-03	L. S. & M. S.	Toledo	Elkhart	133.4	1 : 54 : 00	70.20	4	500,000	4-4-0	20×28	80	133,000	172,000	5-29-03
6-19-03	L. & N. W.	London	Carlisle	299.2	5 : 58 : 00	50.14	12	Note	Note					7-17-03
8- 8-03	A., T. & S. F.	Chicago	Los Angeles	2,267	52 : 49 : 00	42.80	2							8-14-03
4-27-04	Mich. Cent.	Niagara Falls	Windsor	225.7	3 : 18 : 00	68.38	4	334,900	4-4-2	21×26	79	95,000	176,000	5-20-04
6- 9-04	Gt. Western	Plymouth	London	246.8	3 : 46 : 48	65.30		300,000	4-2-2	Note	92			6- 3-04
7-20-04	Atlantic City	Camden	Atlantic City	55.5	0 : 43 : 00	77.40	5							8- 5-04
5-14-05	Atlantic City	Atlantic City	Camden	55.5	0 : 42 : 33	78.26	5	460,000	4-4-2	21×24		99,000		12-15-05
6- 8-05	Penn	East Tolleston	Donaldson	50	0 : 38 : 00	79.00	3		4-4-2	20½×26		109,000		12-15-05
6-13-05	L. S. & M. S.	Chicago	Buffalo	525	7 : 33 : 00	69.53	3	350,000						12-15-05
0- 0-05	N. Y. C. L. S. & M. S.	New York	Chicago	964	18 : 00 : 00	53.55		Note						12-15-05
7- 9-05	A., T. & S. F.	Los Angeles	Chicago	2,246	44 : 54 : 00	50	3	338,000						12-15-05
10-23-05	Sou. Pac. Union Pac. C. & N. W. L. S. & M. S. Erie	Oakland	Jersey City	3,239	73 : 12 : 00	44.30								12-15-05
10-24-05	Penn. Lines	Crestline	Ft. Wayne	131.4	1 : 41 : 20	77.81	4	520,000						12-15-05
10-24-05	Penn. Lines	Crestline	Clarke Junction	257.4	3 : 27 : 20	74.55								
11- 3-05	Penn	Harrisburg	Chicago	717	12 : 49 : 00	56	3		4-4-2				Note	12-15-05
5- 5-06	Sou. Pac. Union Pac. C. & N. W. L. S. & M. S. N. Y. C.	Oakland	New York	3,255	71 : 27 : 00	45.60	3	Note						5-18-06
6-19-06	Atlantic City	Camden	Atlantic City	55.5	0 : 43 : 30	76.70	6	Note	4-4-2	20×27	86	110,000	210,000	6-22-06

* Date reported in Railroad Gazette.

53.3 miles an hour and with remarkable punctuality. Some of the records above 80 miles an hour lack the elements necessary to make them entirely credible.

It will be observed that the notable performance of October 24, 1895, which made a number of records that stood unsurpassed for years, was set aside by another performance equally remarkable just ten years later — October 24, 1905.

Table II shows the best records for given distances. They are classified by speeds alone, no account being taken of the modifying effects of load or grade, or size of engine. It will be borne in mind that these records are all those of steam locomotives. For distances under 15 miles, the electric locomotive which was tried on the Berlin-Zossen line in Germany in 1903 made speeds over 130 miles an hour which have not yet been equaled by any steam locomotive.

TABLE II. — BEST RECORDED SPEEDS OF STEAM LOCOMOTIVES

(Locomotive Dictionary)

	Distance, Miles.	Rate, Miles per Hour.	Date.	Road.
1	3,255	45.60	May 5, 1906	Various.
2	2,246	50.00	July 9, 1905	A. T. & S. F.
3	1,025	54.27	Feb. 15, 1897	C. B. & Q.
4	717	56.00	Nov. 3, 1905	Penn.
5	525	69.53	June 13, 1905	L. S. & M. S.
6	257	74.55	Oct. 24, 1905	Penn.
7	131	77.81	Oct. 24, 1905	Penn.
8	55.5	78.26	May 14, 1905	Atlantic City.
9	50	79.00	June 8, 1905	Penn.
10	15	98.66	Mar. 24, 1902	C. B. & Q.
11	4.8	107.90	Mar. 1, 1901	S. F. & W.

Considering passenger service alone, the crowning achievement of the locomotive designers of the past twenty years has been not speed alone, nor speed and power combined, but speed, power, and reliability. The Pennsylvania trains running daily between Jersey City and Chicago, 905 miles, at 50.9 miles an hour, were on time at destination during the year ending June 11, 1906, 328 times out of 365, or 89.8 per cent of the trips of the year, west bound, and 85.2 per cent of the trips east bound. Of the 37 late arrivals at Chicago 14 were not over 10 minutes late. The New York Central reported for its similar trains a somewhat less favorable record; but the Central fast trains travel at a higher speed, the distance being greater, and the trains were often made up of five, six, or seven cars for a part of the distance.

From a table published in the *Railroad Gazette* of January 12, 1906, page 34, giving the speeds of a large number of regular scheduled trains between London and other English cities, the examples shown in Table III are selected:

TABLE III. — REGULAR ENGLISH EXPRESS TRAINS, 1905

	Railway.	Miles.	Speed, Miles per Hour.
London to —			
Bristol	Great Western	118	59.2
Exeter	Great Western	194	56.7
Plymouth	Great Western	246	55.7
Liverpool	L. & N. W	201	56.1
Nottingham	Midland	125	56.8
Nottingham	Great Central	126	57.5
Sheffield	Great Central	165	58.1
Sheffield	Great Northern	162	57.2

On the two important long lines of Great Britain, the West Coast and the East Coast routes to Scotland, the best schedules in effect in 1909 were as follows: London & North Western and Caledonian, London to Glasgow (midnight train), 401.5 miles; 8 hours; rate, 50.2 miles an hour. Great Northern, North Eastern and North British, London to Aberdeen (day train), 523.5 miles; 11 hours, 7 minutes; rate, 47.1 miles an hour.

Table IV below shows the best performances of American railroads. The fast trains between New York and Philadelphia, which for years were notable as the fastest trains in America, are now outclassed by the New York-Chicago trains. The Pennsylvania's Chicago train is regularly scheduled from Jersey City to North Philadelphia, 84 miles, in 83 minutes.

TABLE IV. — SCHEDULED SPEEDS OF FAST REGULAR TRAINS ON AMERICAN RAILROADS, AUGUST, 1906

(Locomotive Dictionary)

	From	To	Railroad.	Distance, Miles.	Time, Hrs. Mins.	Speed, Miles per Hour.
1	Oakland	Chicago	Southern Pacific, Union Pacific, Chicago & North Western	2,274	67:30	33.7
2	Los Angeles.	Chicago	Atchison, Topeka & Santa Fé	2,267	66:15	34.2
3	New York	Chicago	New York Central & Hudson River and Lake Shore & Mich. Southern	964	18:00	53.5
4	Jersey City.	Chicago	Pennsylvania	905	17:46	50.9
5	New York	Buffalo	New York Central	440	8:15	53.3
6	New York	Boston	New York, New Haven & Hartford	232	5:00	46.4
7	Washington.	Jersey City	Pennsylvania	224	4:46	47.0
8	Jersey City.	Washington	Central of New Jersey, Philadelphia & Reading, Baltimore & Ohio	226	4:48	47.1
9	AtlanticCity	Camden	West Jersey & Seashore (Pennsylvania)	59.0	0:52	68.1
10	Camden	Atlantic City	Atlantic City (Philadelphia & Reading)	55.5	0:50	66.6

At the International Railway Congress held at Berne, Switzerland, July 4 to July 16, 1910,* Mr. Blum expressed the opinion that the primary reason for

* Track Strengthening for Increased Weight of Locomotives and Speed of Trains. Bulletin of the International Railway Congress. London and Brussels, 1910, Vol. XXIV, p. 2497.

the strengthening of tracks was not the increase in the speed of the wheel loads but the greater increase in the traffic, particularly freight traffic. The weakest part of the track, the rail joint, was stated to be most fatigued not by the fast trains but by the slower running trains. Speeds of 130.5 miles an hour had actually been attained on a line having a weaker superstructure than that now used for the express lines of the Prussian State Railways without any danger to the track, and but little anxiety need be felt if higher speeds were used on the existing track. That was the opinion of the majority of the railways from which he had elicited opinions.

In calculating the effect of the wheel pressure on the track a speed of 60 miles per hour will be taken for passenger service and 40 miles per hour for freight service. As is seen from the preceding tables these speeds are exceeded in special runs, but from the evidence of tests we may conclude that, at the higher speeds, while the dynamic force of the wheel increases the track possesses at the same time a greater resisting power. This subject will receive further consideration in the following chapters.

4. Weights of Modern Locomotives

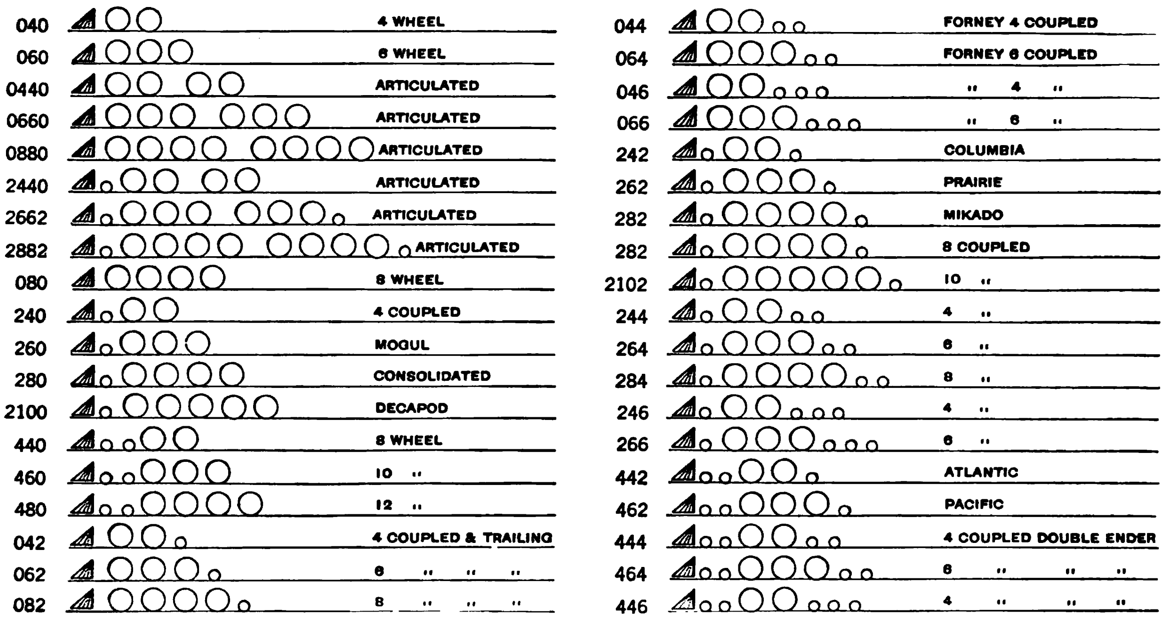


Fig. 3. — Classification of Locomotives (Whyte's System).

The classification given in Fig. 3 will be adopted for the different types of engines under discussion. This locomotive classification is based on the representation by numerals of the number and arrangement of the wheels, commenc-

ing at the front. Thus, 260 means a Mogul, and 460 a ten-wheel engine; the cipher denoting no trailing truck is used.

The total weight is expressed in 1000 of pounds. Thus, an Atlantic locomotive weighing 176,000 pounds would be classified as a 442–176 type. If the engine is compound, the letter C should be substituted for the dash; thus, 442C 176 type. If tanks are used in place of a separate tender, the letter T should be used in place of the dash. Thus, a double-end suburban locomotive with two-wheeled leading truck, six drivers, and six-wheeled rear truck, weighing 214,000 pounds, would be a 266T 214 type.

The locomotives shown in Fig. 4 give an idea of the progress in engine building from 1832 to 1911. The three engines shown in the illustration were

FIG. 4. — Progress in Locomotive Building.

built by the Baldwin Locomotive Works. The engine in the upper figure of the illustration was the Old Ironsides, built in 1832, and weighed in working order about four and a half tons. The engine built in 1876 weighed 103,000 pounds exclusive of the tender and had 22,250 pounds on each driving-wheel axle, while the modern locomotive appearing in the lower figure weighs 462,450 pounds exclusive of the tender and has axle loads exceeding 50,000 pounds. Fig. 5 shows a further comparison of early and modern locomotives.

The following tables illustrate the extent of development that has taken place in the Pennsylvania locomotives from 1850 to 1910.*

* Paper on Scientific Management of American Railways by S. M. Felton, at the Congress of Technology held at Boston, Mass., on April 10, 1911, under the auspices of the Massachusetts Institute of Technology.

	1860	1910
Passenger Locomotives.		
	Lbs.	Lbs.
Weight on each driving axle (approx.)	7,500	59,500
Weight on all drivers	15,000	178,500
Weight on trucks	30,000	93,500
Weight, total	45,000	272,000
Freight Locomotives.		
Weight on each driving axle (approx.)	13,000	54,100
Weight on all drivers	26,000	216,450
Weight on trucks	19,000	24,495
Weight, total	45,000	240,945

Since 1910 the weight of the Pacific type passenger engine shown in the table has been increased from 272,000 pounds to 292,000 pounds by the introduction of superheaters and mechanical stokers, in the case of some engines. The Pennsylvania Railroad also have running a Pacific type engine, built in 1912, weighing 317,000 pounds which has axle loads of about 66,000 or 67,000 pounds, and an experimental Atlantic type engine with 68,800 pounds on an axle.

In Tables V to XI are given weights and axle loads of modern engines. The passenger engines are noticeable for their trailing trucks and four-wheel leading trucks, while the freight engines commonly use a two-wheel leading truck and no trailer, although the Mikado type (282) is designed with the trailing truck. This engine is a comparatively new development, and is not shown in the tables. It is rapidly coming into favor for heavy freight service in which the Consolidation locomotive was formerly employed.

The weight of the engine can, of course, be determined accurately. The maximum rail pressure of a driving wheel when the locomotive is running is, however, not at all indicated by the static load of the wheel on the rail.

Fig. 5. — Decapod Locomotive of 1903 and American Type of 1857. (Railway Age Gazette.)

The dynamic augment * is due to several causes: First, the effect of the "excess balance" necessary to counteract the reciprocating parts is to cause an impressed load. Second, the angularity of the main rod causes an increase of pressure on the main wheel. Third, consideration of impact or imperfections existing in the rolling stock or roadway. Fourth, the rocking of the engine on its springs.

TABLE V. — AXLE LOADS AND TOTAL WEIGHTS OF ATLANTIC TYPE (442) LOCOMOTIVES

(From data furnished by the American Locomotive Company)

Name of railroad	Wabash	Oregon Short Line	Southern	Rock Island
Works	Brooks	Brooks	Richmond	Schenectady
Weight on leading truck, pounds	42,000	47,500	42,000	49,000
Weight on driving wheels, pounds	111,000	99,500	114,500	116,000
Weight on trailing truck, pounds	38,000	48,000	39,500	37,000
Weight, total of engine, pounds	191,000	195,000	196,000	202,000
Weight of tender, pounds	130,000	142,500	144,500	150,000
Wheel base, driving	7′ 6″	7′ 0″	7′ 6″	7′ 0″
Wheel base, total of engine	30′ 11½″	27′ 7″	29′ 6″	30′ 10″

TABLE VI. — AXLE LOADS AND TOTAL WEIGHTS OF PACIFIC TYPE (462) LOCOMOTIVES

(From data furnished by the American Locomotive Company)

Name of railroad	C., M. & St. P.	Vandalia	N. Y. C.	Pa. Lines
Works	Brooks	Schenectady	Schenectady	Pittsburg
Weight on leading truck, pounds	43,200	49,500	48,000	48,000
Weight on driving wheels, pounds	167,300	162,000	170,500	176,500
Weight on trailing truck, pounds	41,300	44,500	48,000	45,500
Weight, total of engine, pounds	251,800	256,000	266,500	270,000
Weight of tender, pounds	152,600	145,900	164,500	144,000
Wheel base, driving	14′ 0″	13′ 10″	14′ 0″	13′ 10″
Wheel base, total of engine	35′ 7″	34′ 8½″	36′ 6″	35′ 2½″

* See Rail Pressures of Locomotive Driving Wheels. Barnes. Trans. Am. Soc. Mech. Engrs., Vol. XVI, 1895, pp. 249–289.

TABLE VII. — AXLE LOADS AND TOTAL WEIGHTS OF PRAIRIE TYPE (262) LOCOMOTIVES

(From data furnished by the American Locomotive Company)

Name of railroad	C., B. & Q.	P. L. W. of P.	P. R. R.	L. S. & M. S.
Works	Brooks	Schenectady	Schenectady	Brooks
Weight on driving wheels, pounds	158,000	163,000	167,000	170,000
Weight on leading truck, pounds	25,500	26,500	27,000	28,000
Weight on trailing truck, pounds	33,500	40,500	40,500	47,000
Weight, total of engine, pounds	217,000	230,000	234,500	245,000
Weight of tender, pounds	148,500	140,000	139,500	159,000
Wheel base, driving	13′ 4½″	14′ 0″	14′ 0″	14′ 0″
Wheel base, total of engine	30′ 8½″	34′ 3″	34′ 3″	34′ 3″

TABLE VIII. — AXLE LOADS AND TOTAL WEIGHTS OF TEN-WHEEL TYPE (460) LOCOMOTIVES

(From data furnished by the American Locomotive Company)

FREIGHT LOCOMOTIVES

Name of railroad	C. & N. W.	D. N. W. & P.	St. L. & S. F.	C. P. R.
Works	Schenectady	Schenectady	Brooks	Montreal
Weight on driving wheels, pounds	135,000	143,000	142,000	143,000
Weight on leading truck, pounds	46,000	47,000	50,000	52 000
Weight, total of engine, pounds	181,000	190,000	192,000	195,000
Weight of tender, pounds	143,500	149,000	127,000	131,000
Wheel base, driving	14′ 10″	14′ 10″	14′ 10″	14′ 10″
Wheel base, total of engine	25′ 10″	25′ 9″	25′ 9″	26′ 1″

PASSENGER LOCOMOTIVES

Name of railroad	Ore. R. R. & Nav. Co.	N. Y. C.	D. N. W. & P.	D., L. & W.
Works	Brooks	Schenectady	Schenectady	Schenectady
Weight on driving wheels, pounds	161,000	158,000	161,500	170,000
Weight on leading truck, pounds	44,000	51,000	49,500	48,000
Weight, total of engine, pounds	205,000	209,000	211,000	218,000
Weight of tender, pounds	164,000	148,000	142,000	135,500
Wheel base, driving	13′ 10″	15′ 10″	14′ 10″	14′ 4″
Wheel base, total of engine	25′ 10″	26′ 10½″	25′ 9″	25′ 6″

TABLE IX. — AXLE LOADS AND TOTAL WEIGHTS OF MOGUL TYPE (260) LOCOMOTIVES

(From data furnished by the American Locomotive Company)

Name of railroad	K. C., M. & O.	So. Pacific	D., L. & W.	Vandalia
Works	Pittsburg	Brooks	Schenectady	Schenectady
Weight on driving wheels, pounds	148,000	150,000	156,500	159,000
Weight on leading truck, pounds	25,000	27,000	21,000	28,000
Weight, total of engine, pounds	173,000	177,000	177,500	187,000
Weight of tender, pounds	146,000	139,000	124,000	144,000
Wheel base, driving	14′ 2″	15′ 2″	15′ 0″	14′ 9″
Wheel base, total of engine	23′ 4″	24′ 0″	23′ 10″	23′ 10″

TABLE X. — AXLE LOADS AND TOTAL WEIGHTS OF CONSOLIDATION TYPE (280) LOCOMOTIVES

(From data furnished by the American Locomotive Company)

Name of railroad	Mich. Cen.	C., I. & S.	Union R. R.	D. & H.
Works	Schenectady	Brooks	Pittsburg	Schenectady
Weight on driving wheels, pounds	215,500	214,000	226,000	223,000
Weight on leading truck, pounds	25,500	27,500	25,000	29,000
Weight, total of engine, pounds	241,000	241,500	251,000	252,000
Weight of tender, pounds	154,000	148,000	136,000	151,000
Wheel base, driving	17′ 6″	17′ 3″	15′ 7″	17′ 0″
Wheel base, total of engine	26′ 5″	26′ 5″	24′ 4″	25′ 11″

TABLE XI. — AXLE LOADS AND TOTAL WEIGHTS OF FOUR-CYLINDER ARTICULATED COMPOUND LOCOMOTIVES

(From data furnished by the American Locomotive Company)

Type	0660	2662	2882	0880
Name of railroad	B. & O.	C. & O.	St. L. & S. F.	D. & H.
Works	Schenectady	Schenectady	Schenectady	Schenectady
Weight on driving wheels, pounds	334,500	324,000	360,000	445,000
Weight on leading truck, pounds	....	22,000	25,500	....
Weight on trailing truck, pounds	....	46,000	32,500	....
Weight, total of engine	334,500	392,000	418,000	445,000
Weight of tender	139,000	163,000	150,000	167,000
Wheel base, driving	10′ 0″ & 10′ 0″	10′ 0″ & 10′ 0″	15′ 6″ & 15′ 6″	14′ 9″ & 14′ 9″
Wheel base, total of engine	30′ 8″	48′ 10″	56′ 10″	40′ 2″

5. Effect of Excess Balance and Angularity of Main Rod

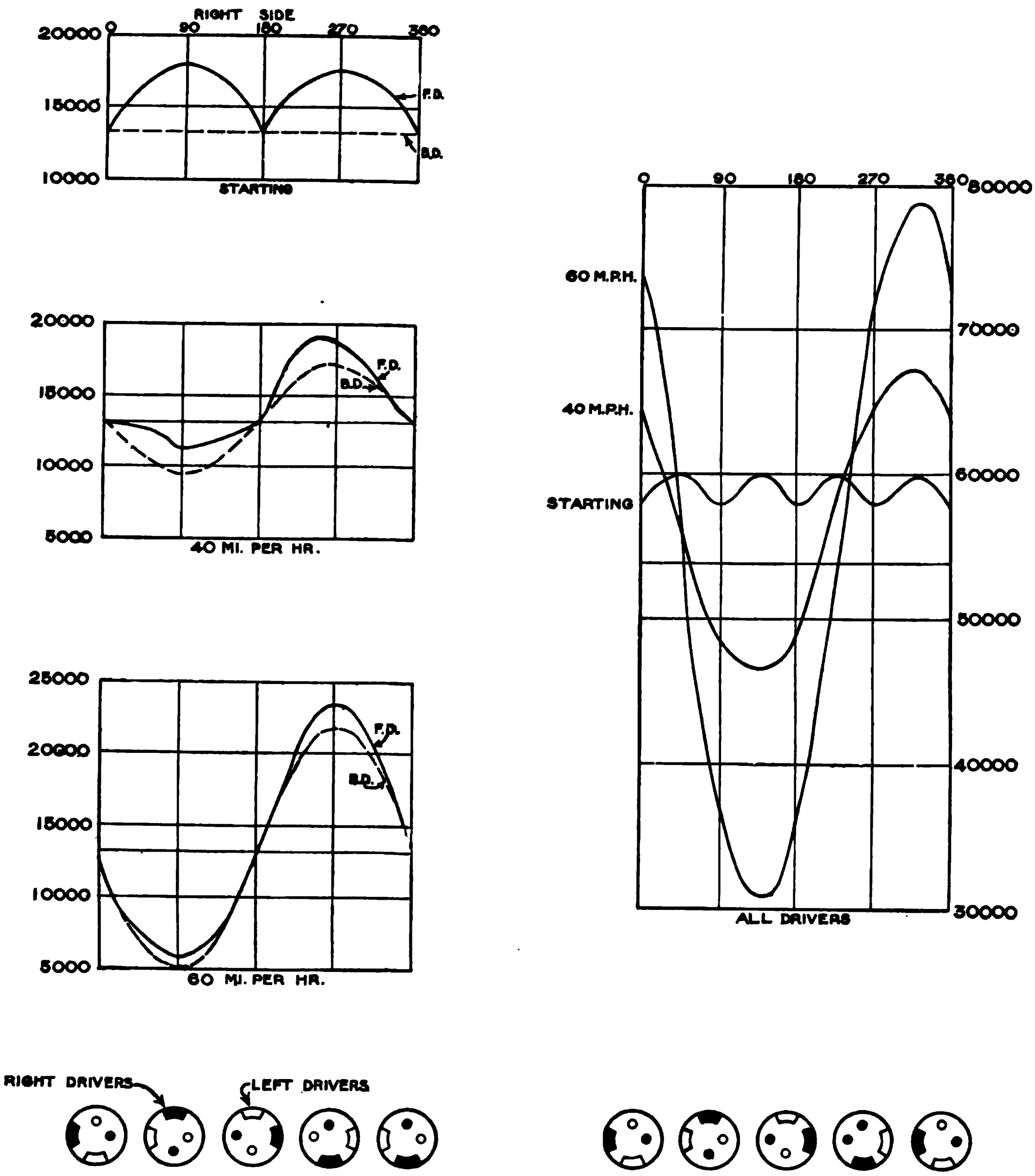


Fig. 6. — Rail Pressures. Eight-wheel Engines. (Am. Ry. M. M. Assn.)

The effect of the excess balance and the angularity of the main rod can be accurately calculated, and is shown on the diagrams given in Figs. 6 to 12.* The calculation for the diagrams given on Figs. 6 and 7 were all made from

* Figs. 6 and 7 are taken from Proceedings Am. Ry. M. Mech. Assn., 1895. Figs. 8 to 12 are from data kindly furnished by the American Locomotive Co.

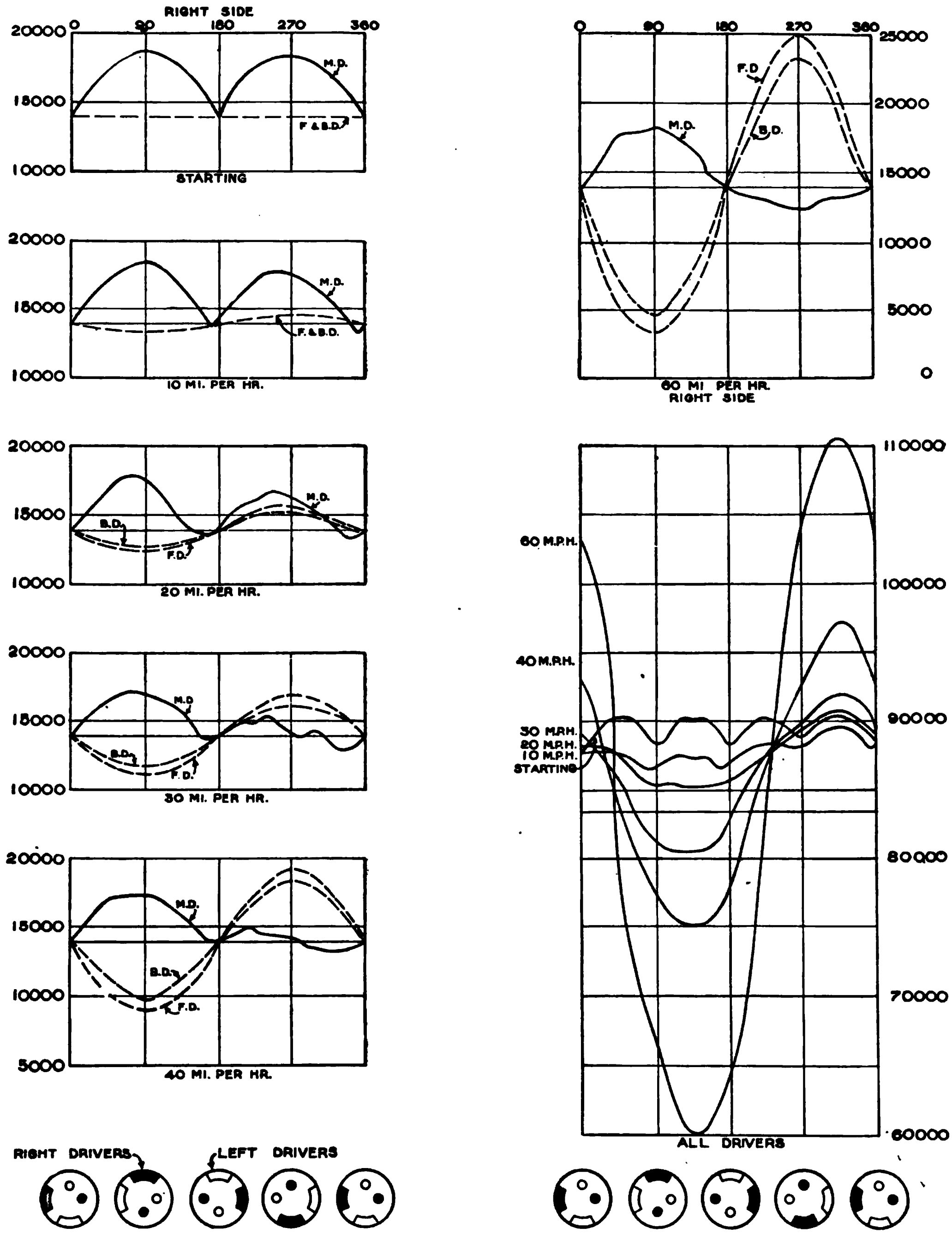


FIG. 7. — Rail Pressures. Ten-wheel Engines (Light Weights). (Am. Ry. M. M. Assn.)

data obtained from eight- and ten-wheel engines on the C. M. & St. P. Ry. The following are the principal dimensions and weights of each *

* Report of Committee on the Wear of Driving-Wheel Tires, Proceedings Am. Ry. M. Mech. Assn., 1895.

	Eight-wheel Engine.	Ten-wheel Engine.
Cylinders	16 by 24 inches	19 by 26 inches
Steam pressure	160 pounds	150 pounds
Diameter driving centers	56 inches	56 inches
Driving wheel base	8 feet, 6 inches	....
Length of main rod	7 feet, $2\frac{1}{8}$ inches	10 feet
Diameter piston rod	$2\frac{3}{4}$ inches	$3\frac{1}{4}$ inches
Weight of reciprocating parts, each side	480 pounds	729 pounds
Weight on drivers	54,000 pounds	84,000 pounds

The piston, piston rod, crosshead, and front end of the main rod are taken as reciprocating parts, the back end of main rod as a revolving weight, in all calculations which follow.

The weights of the ends of the rods were found by supporting each end at the center of the box or bearing, and resting them alternately on scales.

The eight-wheel engines had the entire weight of the reciprocating parts balanced, by adding one-half this weight in each driving wheel to the weight necessary to balance the revolving parts when weighed at the crank pin. The ten-wheel engines were not counterbalanced alike, but all agreed in having the forward and back wheels overbalanced; that is, with a heavier counterbalance than that required to balance the revolving parts only; while the main wheels of thirty-five of the fifty-three engines from which measurements were taken were underbalanced for the revolving parts alone, and all of them underbalanced according to the rule of adding to the weight necessary to balance the revolving parts two-thirds of the weight of the reciprocating parts, divided equally between the driving wheels.

The counterbalance in the wheels of each of these engines was carefully weighed by resting the journals of each pair of drivers on level straight edges, placing the crank horizontally, and hanging on the crank pin a sufficient weight to just balance the counterbalance opposite. From this weight the weight of the revolving parts attached to that pin was subtracted, the remainder being the amount of overbalance weighed at the crank pin. If the weight of the revolving parts exceeded the weight so found, of course the wheel was underbalanced by the amount of such excess.

The actual average condition of the counterbalance in the wheels of the fifty-three ten-wheelers was as follows:

Average overbalance weighed at the crank pin above that required to balance revolving parts only:

Front wheel	271 pounds overbalance
Main wheel	80 pounds underbalance
Back wheel	237 pounds overbalance.

These weights* are used in the calculations for the ten-wheel engines plotted on Fig. 7.

The following formulæ have been used in calculating the forces in action:

NOTATION

P = Pressure of one driving wheel on rail.
W = Weight of each wheel on rail, engine at rest.
C = Centrifugal force of the excess weight in the counterbalance over that required to balance the revolving parts.
A = Horizontal accelerating (or when negative retarding) force of the reciprocating parts.
P_1 = Pressure against crosshead pin from steam in cylinder.
a = Angle of the crank with the horizontal.
N = Ratio of length of main rod to length of crank.

Hence,
$$P = W - C \sin a + \frac{(P_1 - A)}{\sqrt{\frac{N^2}{\sin^2 a} - 1}}. \tag{1}$$

But,

w = Weight of the excess in the counterbalance over that required to balance the revolving parts.
v = Velocity of the center of gravity of the overbalance.
r = Radius of the center of gravity of the overbalance.
w' = Weight of the reciprocating parts.
v' = Velocity of the crank pin.
l = Length of the crank.
g = The acceleration of gravity, 32.16.

Hence,
$$C = \frac{wv^2}{gr}, \tag{2}$$
$$A = \frac{w'v'^2}{gl} \cos a. \tag{3}$$

Or, by substituting in (1) the values of C and A given in (2) and (3),
$$P = W - \frac{wv^2}{gr} \sin a + \frac{\left(P_1 - \frac{w'v'^2}{gl} \cos a\right)}{\sqrt{\frac{N^2}{\sin^2 a} - 1}}. \tag{4}$$

The above formulæ include the centrifugal force of the overbalance in the drivers, the effect of the acceleration and retardation of the reciprocating parts, and the angularity of the main rod. Formula (3), for the acceleration of the reciprocating parts, assumes that they move as they would were the main rod

* These weights are the equivalent weights at a distance from the center equal to the crank length, and not the actual counterbalance weights used.

infinitely long, but the error this produces is too small to affect the accuracy of the results, while the formulæ are much simplified.

The left-hand ends of the diagrams correspond to the position of the engine when the right crank is on the forward center, positive rotation being that produced by running the engine forward.

The pressures upon the piston used in the calculation for Figs. 6 and 7 were obtained from actual indicator cards taken at these speeds, and with a point of cut-off found by the examination of a large number of cards to be the usual point at which an engine is worked at the speed taken.

The points of cut-off used are:

Eight-wheel engine, just starting, 22 inches; 40 miles per hour, 6 inches; 60 miles per hour, 6 inches.

Ten-wheel engine, just starting, 22 inches; 10 miles per hour, 13 inches; 20 miles per hour, 11 inches; 30 miles per hour, 8 inches; 40 miles per hour, 6 inches; 60 miles per hour, $5\frac{3}{8}$ inches.

Curves for just starting, ten and twenty miles per hour, show that the total pressure of the main driver on the rail is always greater at these speeds and cut-offs than the actual weight of driver on the rail when the engine is at rest.

FIG. 13. — Damaging Effect of Badly Balanced Locomotive.

This is due to the angularity of the main rod always causing an increase of pressure on the main wheel. There is, of course, a corresponding upward pressure on the guide, reducing the weight on the truck.

Figs. 8 to 12 are for heavier engines and are calculated from some of the largest engines that have been built of each type.

Fig. 13 shows the damaging effect upon the track of a badly balanced locomotive.

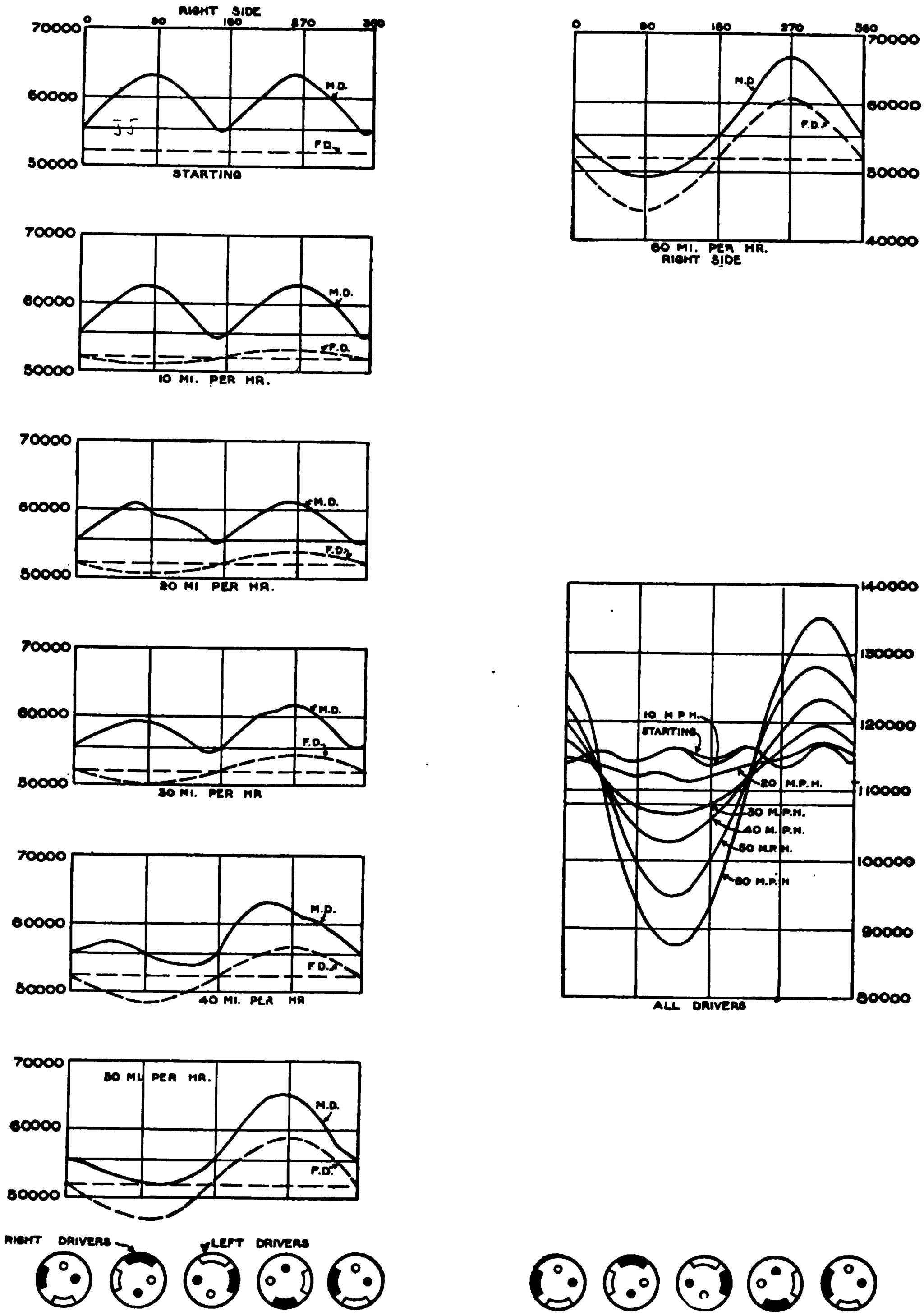


FIG. 8. — **Rail Pressures.** 442 (Atlantic) Type Engines: Cylinders $21\frac{1}{2}'' \times 26''$, Wheels 79″, Working Pressure 180 lbs. (Am. Locomotive Co.)

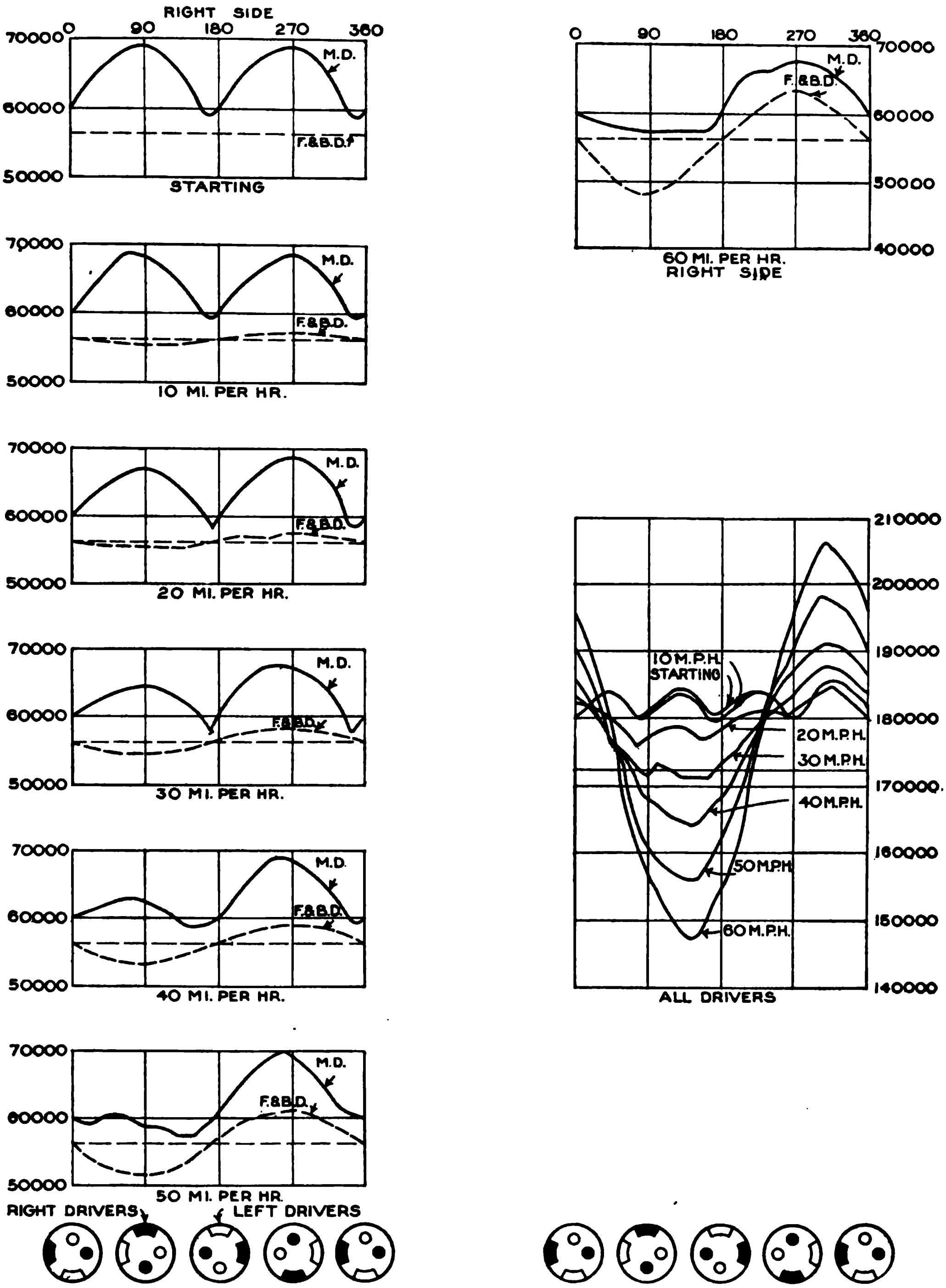


FIG. 9. — Rail Pressures. 462 (Pacific) Type Engines: Cylinders 22" × 28", Wheels 79", Working Pressure 200 lbs. (Am. Locomotive Co.)

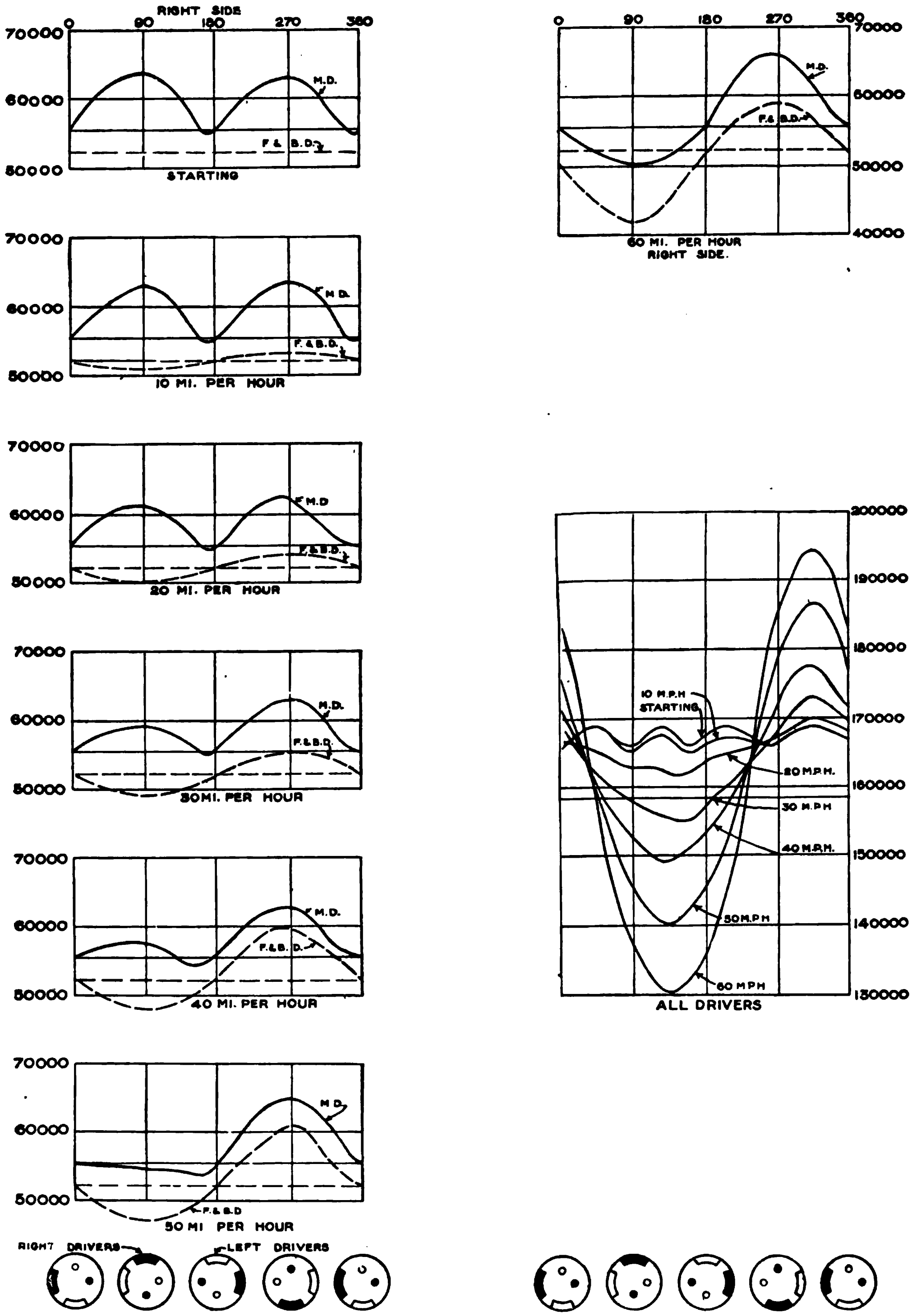


Fig. 10. — Rail Pressures. 460 (Ten-wheel) Type Engines (Heavy Weights): Cylinders 22″ × 26″, Wheels 69″, Working Pressure 200 lbs. (Am. Locomotive Co.)

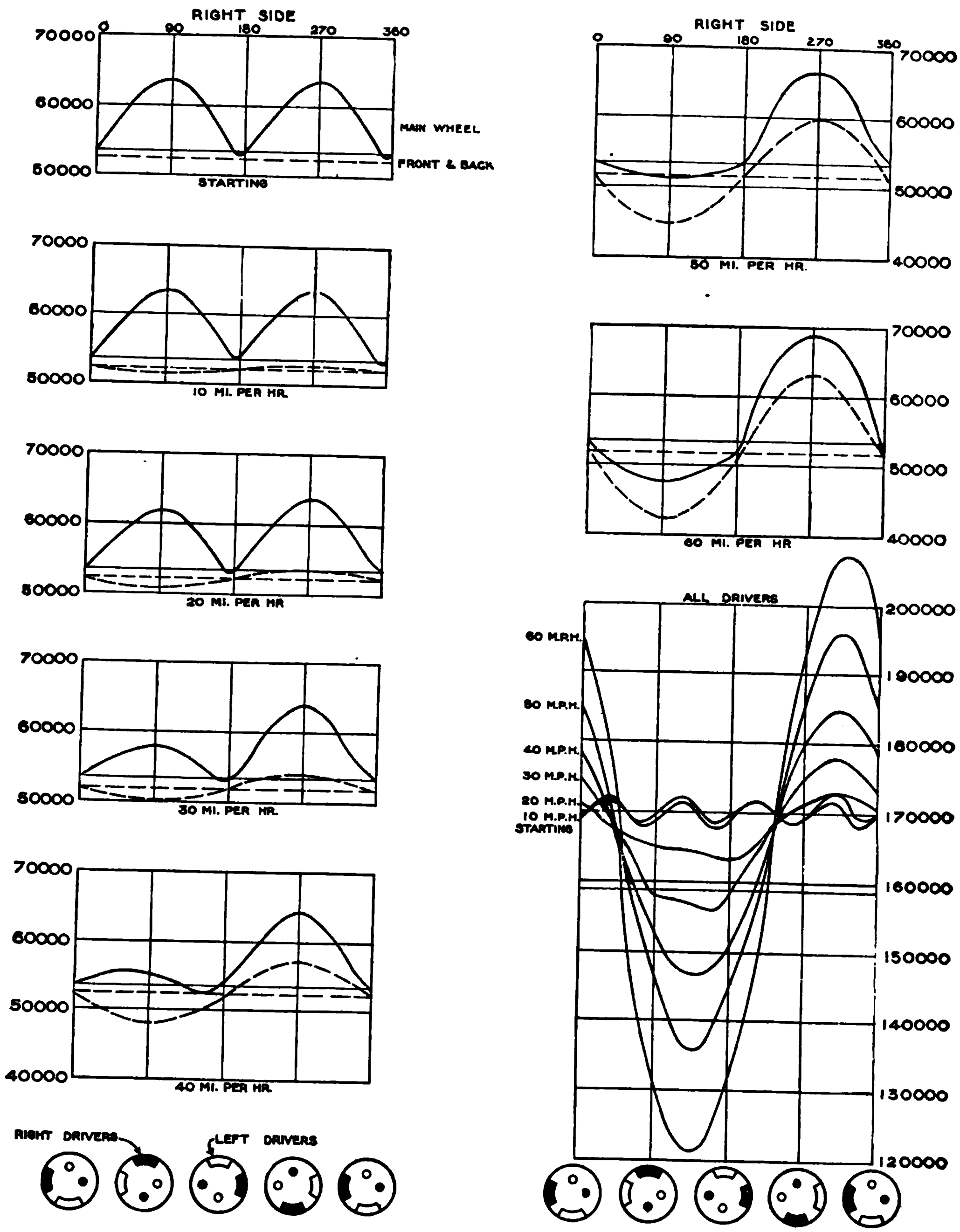


FIG. 11. — Rail Pressures. 260 (Mogul) Type Engines: Cylinders 21″ × 28″, Wheels 63″, Working Pressure 200 lbs. (Am. Locomotive Co.)

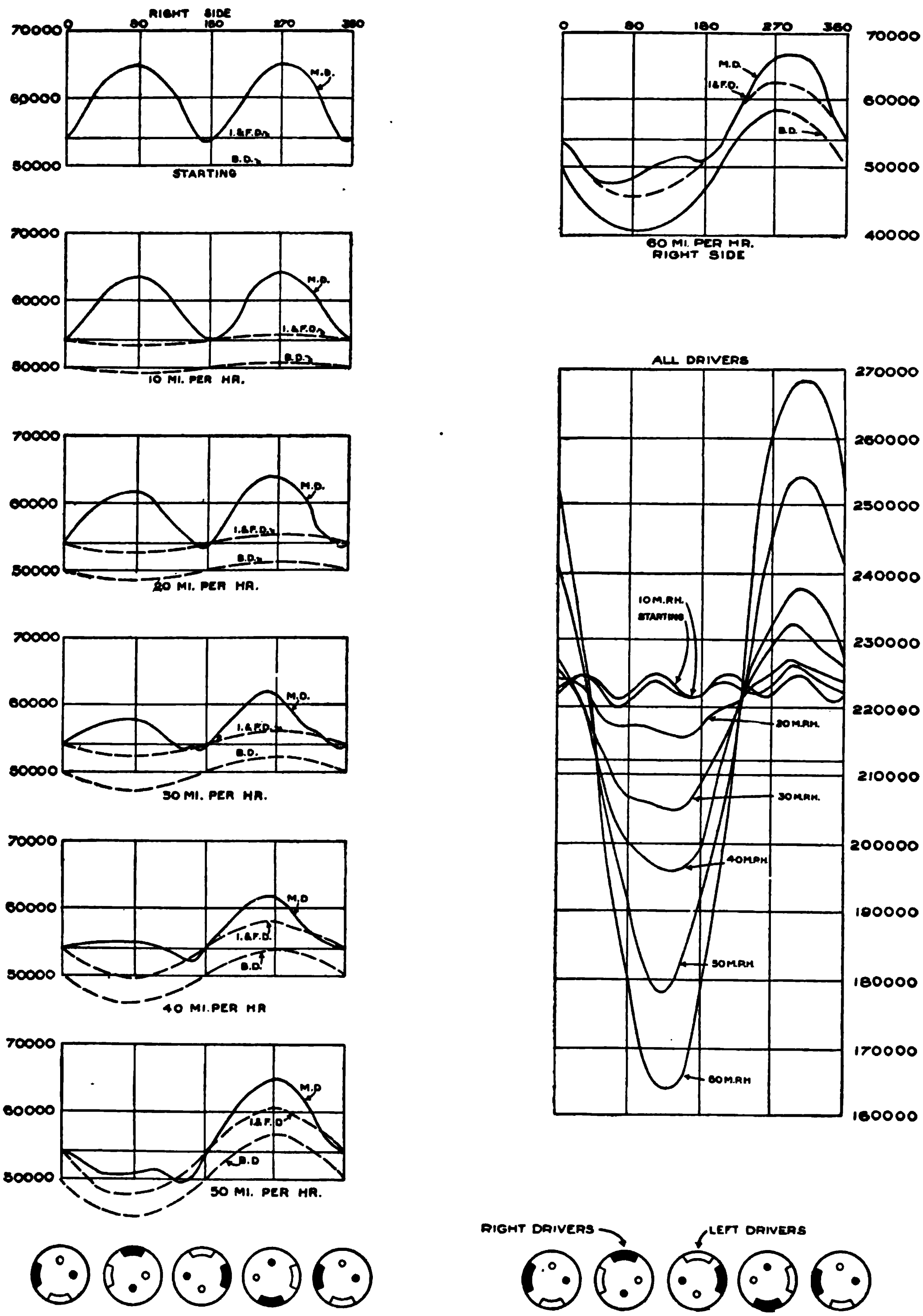


Fig. 12. — Rail Pressures. 280 (Consolidation) Type Engines: Cylinders 23″ × 32″, Wheels 63″, Working Pressure 200 lbs. (Am. Locomotive Co.)

6. Effect of Irregularities in the Track

Fig. 14 shows the exaggerated profile of the rail observed by M. Cuënot in his track experiments.

Figs. 15 and 16 show the rail profile taken with a Railroad Automatic Track Inspector machine. These diagrams show the unloaded profile of the rail, or the permanent set left in it by the passage of the trains. Evidently the loaded profile will be below the unloaded line, and both profiles will probably show the same general features, as indicated by the approximate loaded position of the rail shown by the dotted line in Fig. 16.

The wheel as it passes over the curved surface of the rail shown in the figure is constrained to move in a curved path whose radius is about 5000 feet, and the pressure of the wheel on the rail is the centrifugal force, $C = \frac{Mv^2}{R}$, directed away from the center of curvature. For 30,000-pound wheel loads, $M = \frac{W}{g} = \frac{30{,}000}{32.16}$, where the units are in pounds and feet.

For 60 miles per hour,

$$v = \frac{5280 \times 60}{60 \times 60} = 88 \text{ feet per second,}$$

and

$$R = 5000.$$

Therefore

$$C = \frac{Mv^2}{R} = \frac{30{,}000 \times 88 \times 88}{32.16 \times 5000} = 1445 \text{ pounds,}$$

which is the excess wheel pressure caused by the irregularity in the track shown by the figure. To be on the safe side, it would seem desirable to increase this amount. If, however, 4000 pounds be taken to represent the excess wheel pressure, due to this cause, an ample factor of safety will apparently have been provided.

It will be seen from the above that the increase of wheel pressure, due to any change in the grade line, will be so small as to be negligible. It is good practice to change from one rate of grade to another with a vertical curve, changing the grade at each 100-foot station by 0.1 feet; this would give a radius for the vertical curve of 50,000 feet, and a corresponding value for C of about 150 pounds.

Let us now consider the path of the wheel when passing over the summit between two of the depressions shown in the track profile, Fig. 15. When the wheel is in the act of leaving the valley, or depression, its path lies in a direction away from the surface of the rail before it. It is, however, under the influence of two forces, — neglecting for the moment the action of the springs. First, its

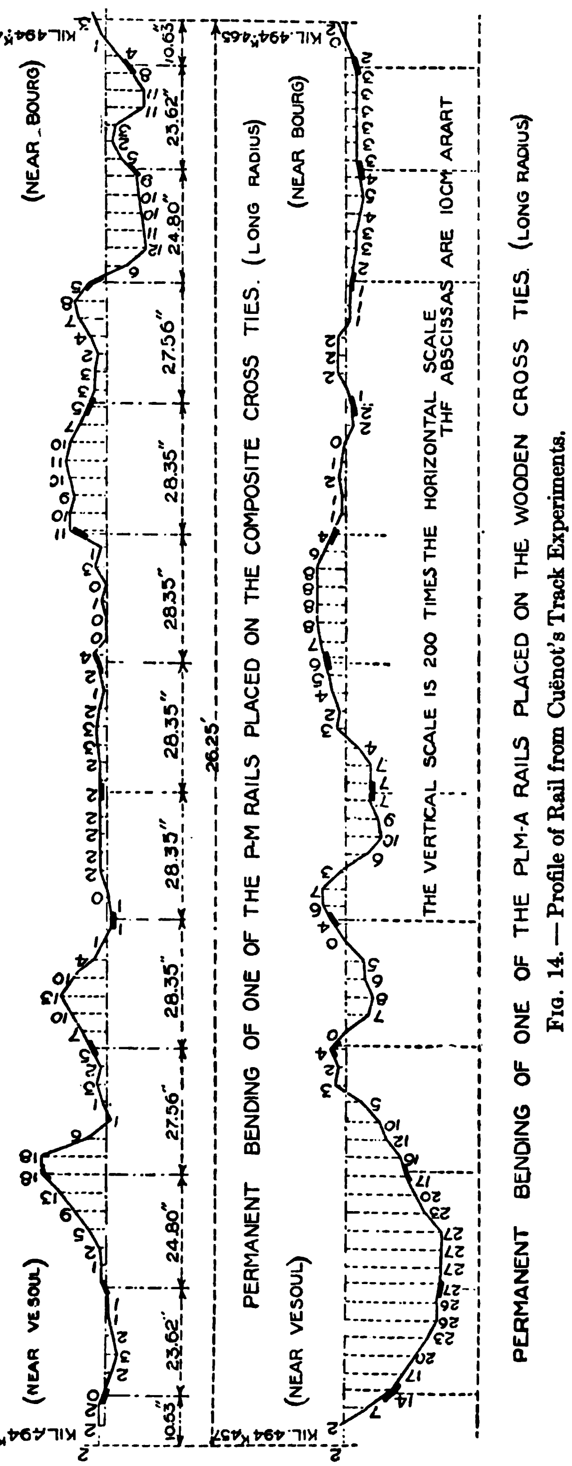


FIG. 14.—Profile of Rail from Cuënot's Track Experiments.

momentum, acting along a line of direction tangent to the vertical curve of the rail; and, second, the force of gravity. The trajectory of the wheel acting under

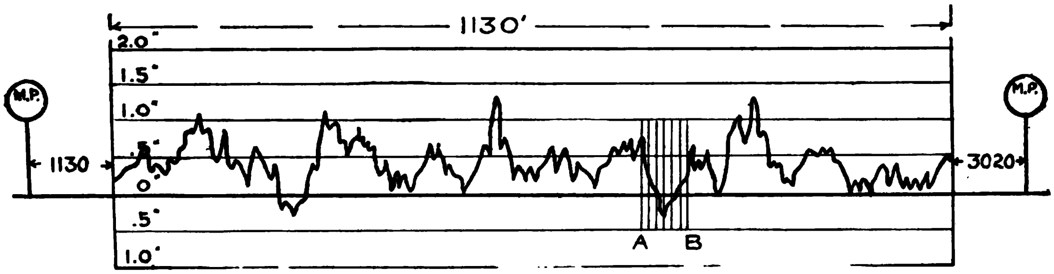


FIG. 15. — Rail Profile taken with a Railroad Automatic Track Inspector Machine.

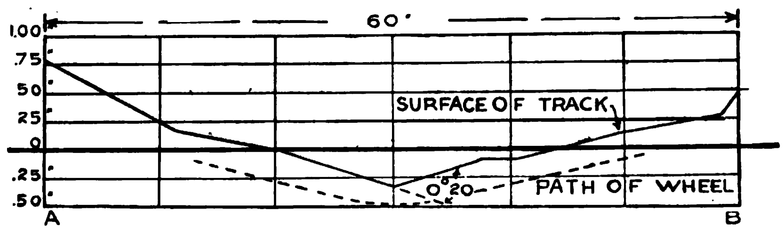


FIG. 16. — "Valley" or Local Depression in Track Profile.

these forces will be a parabola with its axis vertical. The greatest height of ascent, y, and the horizontal range, x, are given by the following equations:

$$y = h \sin^2 a,$$
$$x = 2h \sin 2a.$$

h being the ideal height due to the velocity, we therefore have for a speed of 60 miles per hour,

$$v^2 = 2gh,$$

or

$$h = \frac{v^2}{2g},$$

$$h = \frac{88 \times 88}{2 \times 32.16} = 121 \text{ feet.}$$

Fig. 17 is derived from the same record as that from which the diagram of Fig. 15 has been taken and shows a summit between two depressions in the profile of the track. We see from the figure that the value of a is 0° 14′. Substituting these values in the expressions for x and y, there results for the greatest height of ascent 0.002 feet, or 0.024 inches, and for the horizontal range, 1.97 feet.

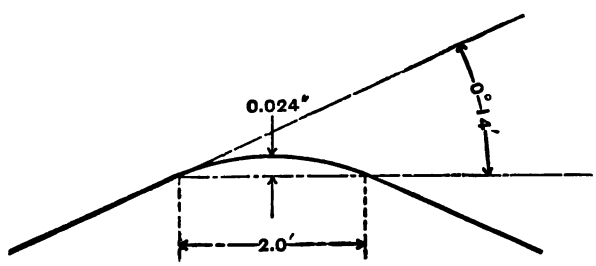


FIG. 17. — Summit between Two Depressions of Track Profile.

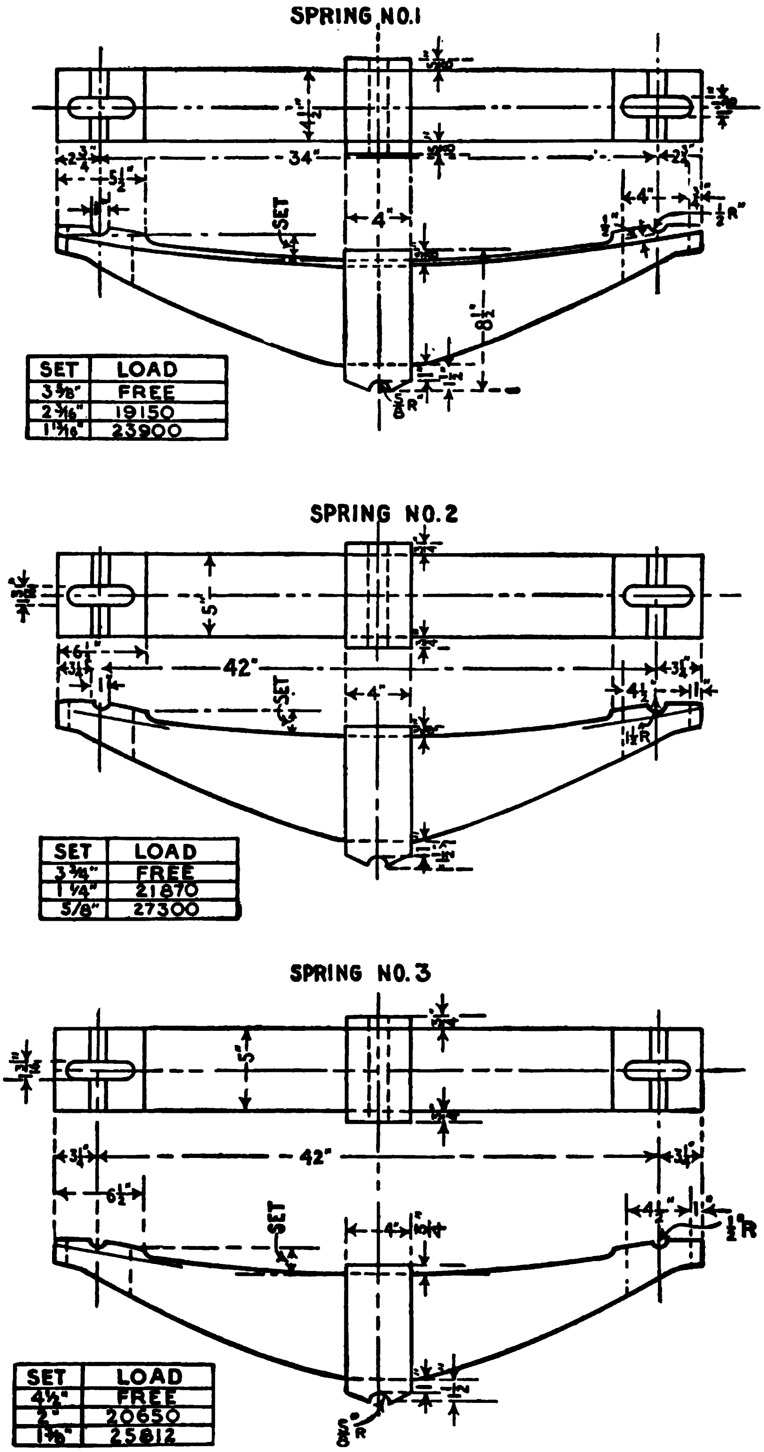


FIG. 18.—Locomotive Driving Wheel Springs.

Fig. 17 shows that this curve practically coincides with the profile of the rail. It is hardly conceivable, therefore, that the wheel can leave the rail when passing from one depression to another, as the action of the springs, as well as the resilience of the rail, which would tend to prevent this, are neglected in the preceding discussion.

7. Effect of Rocking of the Engine

The pressure caused by the rocking of the engine on its springs can best be determined by observing the amount the springs deflect under their load.

By referring to Plates XX and XXI, it will be seen that the wear of the guides of the driving boxes will give a means of telling how much the springs deflect. The maximum amount of wear is probably about one inch. Turning to Figs. 18 and 19, which show the springs used for the locomotive drivers, we see that the depression of the spring one inch corresponds to a range of pressure of about 8000 pounds. However, as the rocking of the engine causes at times a less pressure as well as a greater on the springs, one-half of this amount, or 4000 pounds, should be taken as the pressure which will cause the spring to deflect an amount equal to that obtained under service conditions.

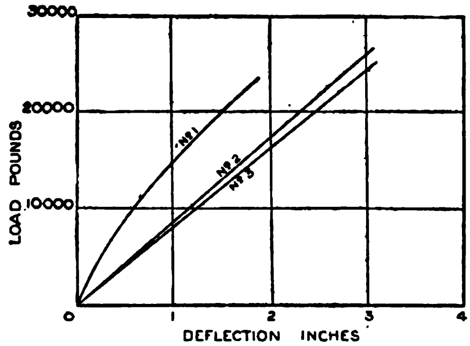


Fig. 19. — Deflection of Locomotive Springs.

A careful series of experiments have been made by Messrs. Coes and Howard * to determine the live load on locomotive driving springs under actual running conditions.

The apparatus consists of three distinct parts: (1) a recording device, which fits on the spring band or saddle; (2) a spanner bar or beam, which is fastened to each end of the spring link hangers and is connected to the recording apparatus; (3) a battery box, which is in the cab with rheostat, switches, keys, clock, and all the necessary controlling mechanism. See Figs. 20, 21, and 22.

The recording apparatus (Fig. 20) is in a box, which is bolted to a steel plate (1) by four bolts; this plate in turn is bolted to a U-shaped band (2) which is fastened to the spring band by four hardened steel set-screws. The record is made on metallic-faced paper, 4 inches wide and about 750 feet long. This paper is wound up upon a detachable drum (3) and travels across a curved brass guide plate (4) under two guide rolls (5) on to the main drum (6).

* Thesis 1906 at the Massachusetts Institute of Technology, under the supervision of Prof. Lanza.

Fig. 20. — Recording Device and Cab Controlling Mechanism for Testing Driving Wheel Springs. (Coes and Howard.)

Fig. 21. — Recording Device in Place on Driving Wheel Spring. (Coes and Howard.)

The main drum is driven by a motor (m) behind the curved plate, through a worm and wheel drive (w). The main stylus is on a steel bar (b) machined to fit two steel boxes (7) and is free to slide up and down. Considerable trouble

FIG. 22. — General Arrangement of Apparatus for Testing Driving Wheel Springs. (Coes and Howard.)

was encountered with the stylus on account of the excessive vibration and jarring, and finally the type shown in Fig. 23 was designed, which gave entire satisfaction, and with which the whole apparatus was equipped.

This is so constructed as to make the stylus spring always work in tension, which is better than using the spring in compression. The spring is sufficiently long to be sensitive and still not be thrown from the plate when the engine strikes a curve, a trouble characteristic of all former instruments. Besides the main stylus there are three others of identical construction. First, the zero stylus (8), which draws a straight line across the roll and to which all deflections are referred; second a stylus (9) which is on a magnet that is operated by a Morse key in the cab; third, a stylus (10) which is on a magnet and is operated automatically by a clock in the cab.

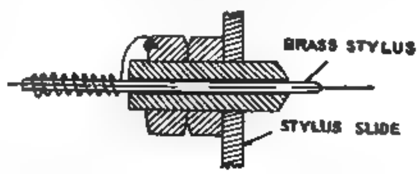


FIG. 23.—Main Stylus used in Driving Wheel Spring Tests. (Coes and Howard.)

The spanner bar (11) is shown in Fig. 21 and needs no description except its method of fastening to the spring link hangers and its mode of operation. It is fastened to the hangers by means of two blocks, which are slotted and fit over the ends of the hangers, these blocks being held on to the hangers by four

hardened steel set-screws. The spanner bar (11) is connected to the stylus bar (*b*) by means of a short link (*Z*). Thus, whatever relative movement is given the recording apparatus by the spring is transmitted as a vertical line on the paper by means of the stylus bar (*b*) and the spanner bar (11). Hence, since the paper is being driven horizontally by the motor we have a wavy line giving a complete record of every movement made by the spring, and by means of the records made by the key and the times recorded by the clock we can account for most of the deflections due to frogs, switches, curves, crossings, brake applications, and bridges.

The cab apparatus (Fig. 20) consists of a suitable box containing a portable storage battery and six dry batteries. The storage battery gives 5 amperes for 8 hours at a pressure of 6.6 bolts. This runs the motor. The six dry batteries operate the clock and the key. On top of the box is a key (*K*), which is connected by means of flexible lamp cord, fastened to the running board, to the magnetic stylus (9). By means of the key the operator can record by code any observation that may be necessary in working up the records. On the side of the box is fastened a clock, which automatically records 15-second intervals on the paper by a magnetic stylus (10). The motor is kept at the proper speed by a rheostat fastened to the top of the box.

The first successful run was made on engine 1064, consolidated type 2-8-0, with 36-inch springs, 17 leaves, 4 full-length leaves 4 inches by $\frac{3}{8}$ inch. This run was made on the Fitchburg Division of the Boston and Maine Railroad from Boston to Ayer Junction on February 17, 1906. The spring tested was the second (counting from the cylinder) on the left side. From this run was obtained a maximum deflection of 0.34 inch. (See Plate XIX.)

A second run was made March 3, 1906, over the same route and on the same engine to see if the same deflections were obtained. The curves obtained by this latter run were practically identical with the test of February 17, 1906. (See Figs. A and B, Plate XIX.) Figs. C D, E, and F present curves taken at other points of the track.

The spring from engine 1064 was taken out and sent to the Engineering Laboratory of the Institute and tested on the 100,000-pound Olsen Machine. The results of this test are plotted and shown on Fig. 24. Two tests were made, one with rollers under the knife-edges and one without. The set had been measured on the engine and the ends of the leaves had also been marked. The spring was then placed in the testing machine and the loads applied, corresponding micrometer readings of the deflections being taken until the spring had been loaded down to the set as measured on the engine.

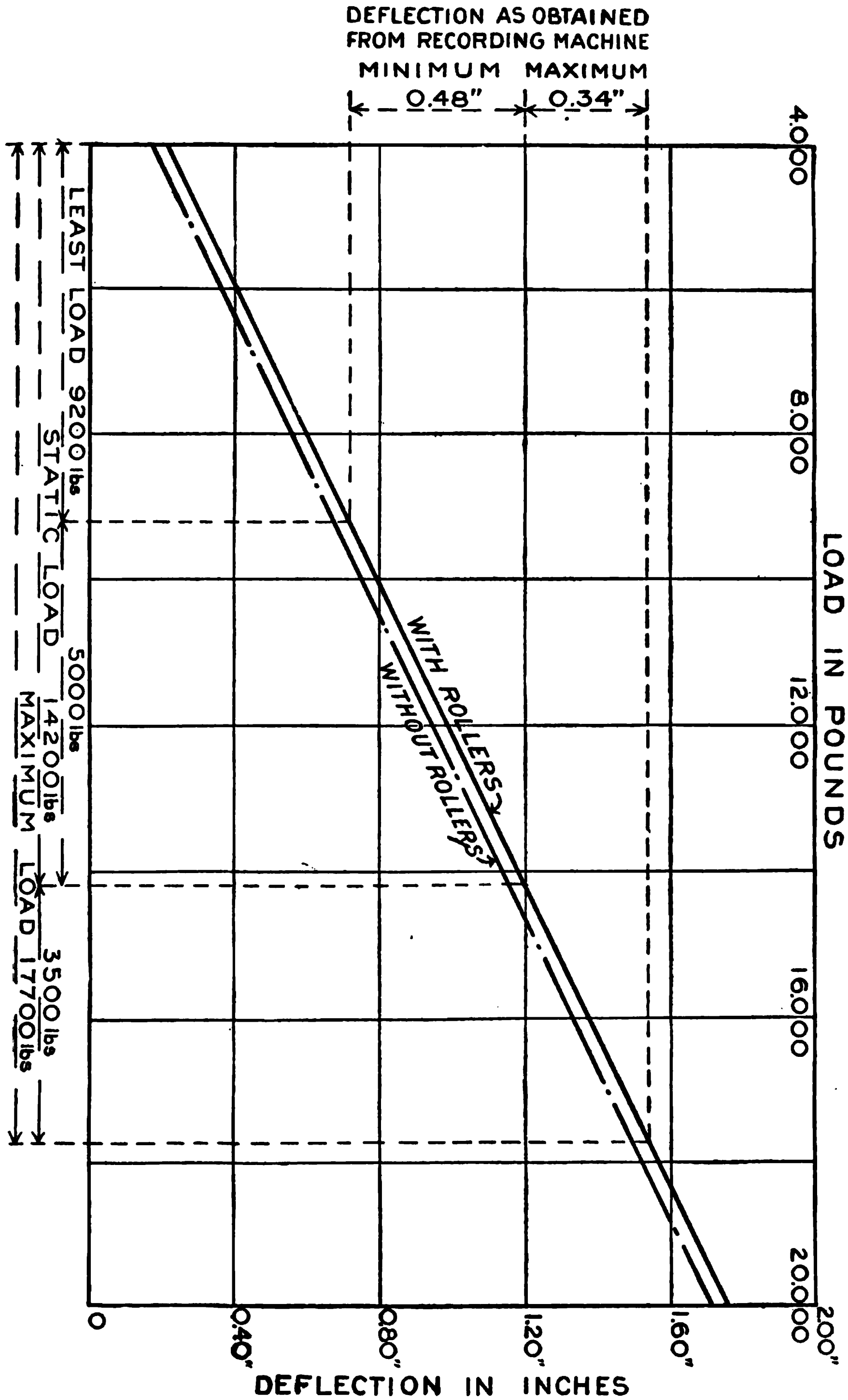


FIG. 24. — Stress-strain Diagram-Locomotive Driving Wheel Springs. (Coes and Howard.)

This load was 14,200 pounds, or the static load on the engine, the dead load for which the spring was designed being 14,144 pounds. Next the maximum deflection, as recorded by the spring apparatus, which was 0.34 inch, was put in the spring, the load corresponding being 3500 pounds gradually applied, making a total load on the spring of 17,700 pounds.

The excess load applied to the engine when running should be classed as a suddenly applied load. If we consider the relation between the load slowly applied to the spring in the testing machine and that suddenly applied when the engine is in service, we see that in the first case the load gradually increases from 14,200 pounds up to 17,700. The average load acting through 0.34 inch is only 15,950 pounds and the total work done on the spring amounts to:

$$15{,}950 \times 0.34 = 5423 \text{ inch-pounds.}$$

In the case of the suddenly applied load under service conditions it will be observed that owing to the load reaching nearly its full intensity before the spring deflects, the load producing the deflection in this case would be obtained by dividing 5423 inch-pounds by the deflection,*

or
$$\frac{5423}{0.34} = 15{,}950 \text{ pounds.}$$

This amounts to 12.3 per cent more than the static load of the engine on the spring (14,200 pounds) and represents the dynamic augment of the spring-borne weight of the locomotive.

It will be noticed that the dynamic augment as determined by these experiments is considerable in excess of the figure arrived at by observing the wear of the guides of the driving boxes. In the latter case the average deflection corresponded to a load in the testing machine of 4000 pounds. Taking half of this or 2000 pounds as the dynamic load producing the same deflection of the spring, we find a dynamic augment to the 25,000-pound static wheel load used of 08 per cent. This may very probably be accounted for by the fact that the maximum deflection obtained is so infrequent as to cause no perceptible wear.

8. Effect of Flat Spots in the Wheels

We have now taken account of all the forces exerted by the wheel on the rail except the impact caused by the existence of flat spots in the tread of the wheel.

The violence of the blow upon the track, delivered at every rotation of the flat wheel, is a matter of common observation; but the amount of its force and the damage done thereby are very hard to determine.

* See Applied Mechanics, Gaetano Lanza, 1895, page 246.

A theoretical discussion of the force of the impact is not likely to lead to any practical results because of the indefiniteness of the shape of the spot, due to the rounding of the corners by wear, also to the lack of knowledge of the effect of the springs and the resilience of the track.

The kinetic energy of the impact is represented by the expression $\frac{1}{2} Mv^2$, where M represents the mass and v the velocity. In order to show a loss of energy there must be a change of velocity, but any perceptible change in the horizontal velocity of a moving car, due to the impact of the flat spot, is quite inconceivable. There may, however, be a change in the vertical velocity of the load as the flat spot comes over the rail.

Professor Hancock, of Purdue University, has made a very careful study of the mathematical relations existing between the speed, impact, and length of spot.*

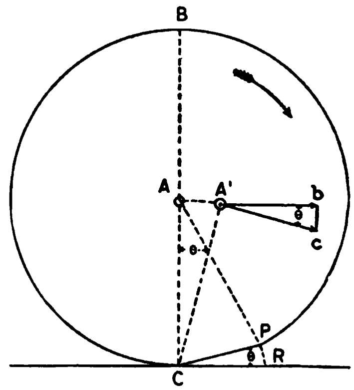


FIG. 25. — Flat Spot in Wheel. (Hancock.)

Following Professor Hancock's analysis, let A, in Fig. 25, be the center of a car wheel D inches in diameter, revolving as shown by the arrow, and CP be a flat spot L inches long just beginning its contact with the rail. The whole wheel is turning about the point C, and will so turn until P reaches R and the blow is struck on the rail. At this latter instant A will have reached A' and will be moving downward with a velocity represented by the line bc. If the velocity of A', which is practically the same as that of the train, is assumed as v feet per second, then

$$bc = v \sin \theta = v \frac{CP}{CB} = v \frac{L}{D}.$$

If we regard the mass of the wheel and its load as concentrated at A and call the total weight W pounds, the kinetic energy of the mass just before the rail is struck will be:

$$E = \tfrac{1}{2} M (bc)^2 = \frac{W}{2g} \times \frac{v^2 L^2}{D^2}.$$

This formula will give for the energy of impact of a flat spot 2.5 inches long in a wheel 33 inches in diameter, carrying a load of 20,000 pounds when the

* Paper read before the Indiana Engineering Society, January, 1908. See also discussion by L. S. Spilsbury, presented by H. H. Vaughan in the American Engineer and Railroad Journal, December, 1908.

train is traveling 60 miles per hour, 13,800 foot-pounds. At this speed it would seem, however, that the results obtained by the formula would be open to question. In the derivation of the formula it is assumed that the wheel turns about C until P reaches R. This assumption only holds true for speeds from zero up to about five miles per hour; * at speeds greater than five miles per hour the point C will tend to leave the rail, and the whole wheel will revolve for an instant entirely clear of the rail.

The above discussion neglects the effect of the springs, which will be to increase the acceleration caused by gravity, and the resilience of the rail, which will cause it to rise to meet the flat spot.

It is very questionable whether, on account of the very small time interval required for the wheel to pass the length of the flat spot,† there is an appreciable increase in the stress in the rail, except at the point of contact of the wheel with the rail.

To increase the load on the rail a change in the vertical velocity of the load must be made; but at high speeds, when the effect of the flat spot is most detrimental, the time required to go the length of the flat spot is so small that the acceleration of the wheel and its load, even when augmented by the action of the springs, is so small as to be negligible. The real danger seems to lie in the metal of the running surface of the head of the rail; the metal here is under a high state of compression (see Figs. 146 and 147), which is momentarily relieved by the passage of the flat spot and then applied suddenly.

When the flat spot is long enough so that the surface of the flat spot is brought in contact with the rail, a sensible change in the vertical movement of the load results and the load on the rail is increased. This is well shown by the following example given by Mr. L. R. Clausen,‡ of the Chicago, Milwaukee & St. Paul Railway:

"Some time in the year 1900 we had an engine with a flat spot on rear right-hand driver 32 inches long and $\frac{7}{32}$ inch deep, which broke about 27 rails during one week's time (85-pound rails, not to exceed one or two years old)".

This flat spot was not apparent to the eye and was only detected by centering the wheel and then measuring around it with a gauge.

* E. E. Stetson, Railroad Age Gazette, December 4, 1908.

† The present allowable length of flat spots in car wheels is 2½ in. This rule was adopted by the Master Car Builders' Association in 1878. In 1909 the question of reducing the limit for freight wheels to less than 2½ inches was considered by committees of the Master Car Builders' Association and the American Railway Engineering Association, but it was not then considered advisable to make any change in the rule.

‡ Proceedings Am. Ry. Eng. & M. of W. Assn., 1909, Vol. 10, Part 2, p. 1158. Report on Flat Spots on Car Wheels.

In the Railway Age Gazette of March 16, 1910, was reported 200 85-pound rails broken in 14 miles by a flat spot which had grown to a length of 6 inches, and a maximum depth of $\frac{3}{8}$ inch. In the extreme cold weather experienced in the months of January and February, 1912, many tires failed by shelling out, and the following examples, taken from the same authority, are representative of the conditions existing on lines in the Northern parts of the country during this period.

Date.	Location.	Tire.	Broken Rails.
January, 1912.	Minnesota.	Flat spot 4 ins. long on a rolled-steel tire in passenger service.	9 80-lb. rails in 3 miles.
January 7, 1912.	Savanna, Ill.	Flat spot $5\frac{1}{2}$ ins. long on steel-tired wheel in passenger service.	150 rails.
January 14, 1912.	South Dakota.	Two steel wheels with flat spots, on different trucks of a dining car.	500 rails.
January 20, 1912.	New York State.	Flat wheel on a fast train.	Nearly 100 rails.
January 24, 1912.	New York State.	Flat wheel on an observation car.	15 rails.
February, 1912.	Ohio.	Shelled-out steel-tired wheel; at end of run the flat spot was 9 ins. long.	960 rails in 200 miles.
February, 1912.	Indiana.	Flat spot on steel-tired wheel under a baggage car.	50 rails in 70 miles.

It is generally known by those familiar with the manufacture and use of chilled car wheels that only a very small percentage of them are evenly chilled. This, apart from weakening the wheel, also produces a lack of roundness tending to cause pounding on the rail. The following information upon tests on the roundness of tread of chilled car wheels has been furnished by Mr. S. K. Dickerson, Assistant Superintendent of Motive Power, and Mr. H. E. Smith, Engineer of Tests, of the Lake Shore and Michigan Southern Railway Company.*

To make these tests six pairs of wheels cast by different founders were selected. An axle with a wheel pressed on each end was placed in a lathe and the centers were firmly pressed. The wheels were then hand-turned. This done, the tread was divided into eight sections, each the same distance from the flat edge, and a specially constructed micrometer used to discover any variations in the roundness. All the testing was done with great care and precision.

The tests are illustrated in Fig. 26. The dotted line in each diagram is a circle through that point on the tread having the smallest radius, and is assumed as the datum line. In plotting the diagram the variations from this datum line have been multiplied by five in order to emphasize the irregularity of the

* Proceedings Am. Soc. for Test. Materials, 1910, Vol. X, p. 307. Unevenly Chilled and Untrue Car Wheels by Thomas D. West.

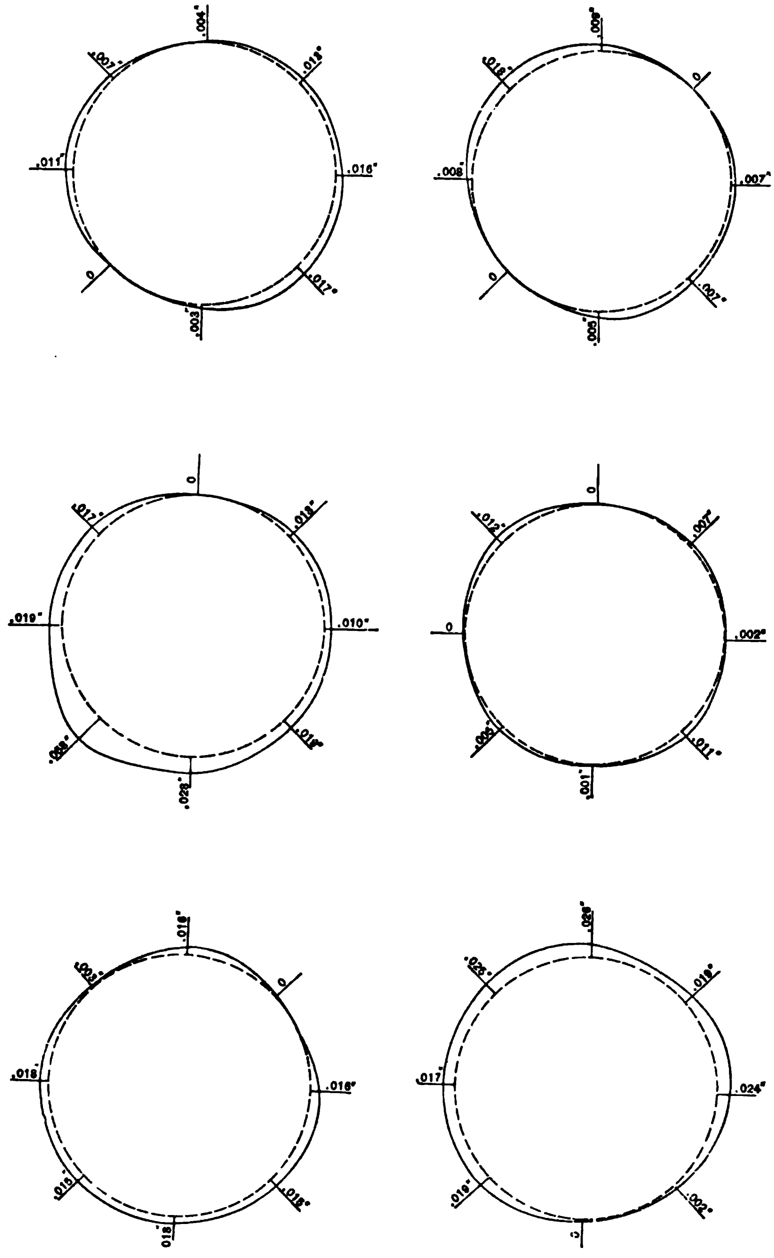


FIG. 26. — Irregularity in the Roundness of Present-day Chilled Car Wheels. (The Iron Age.)

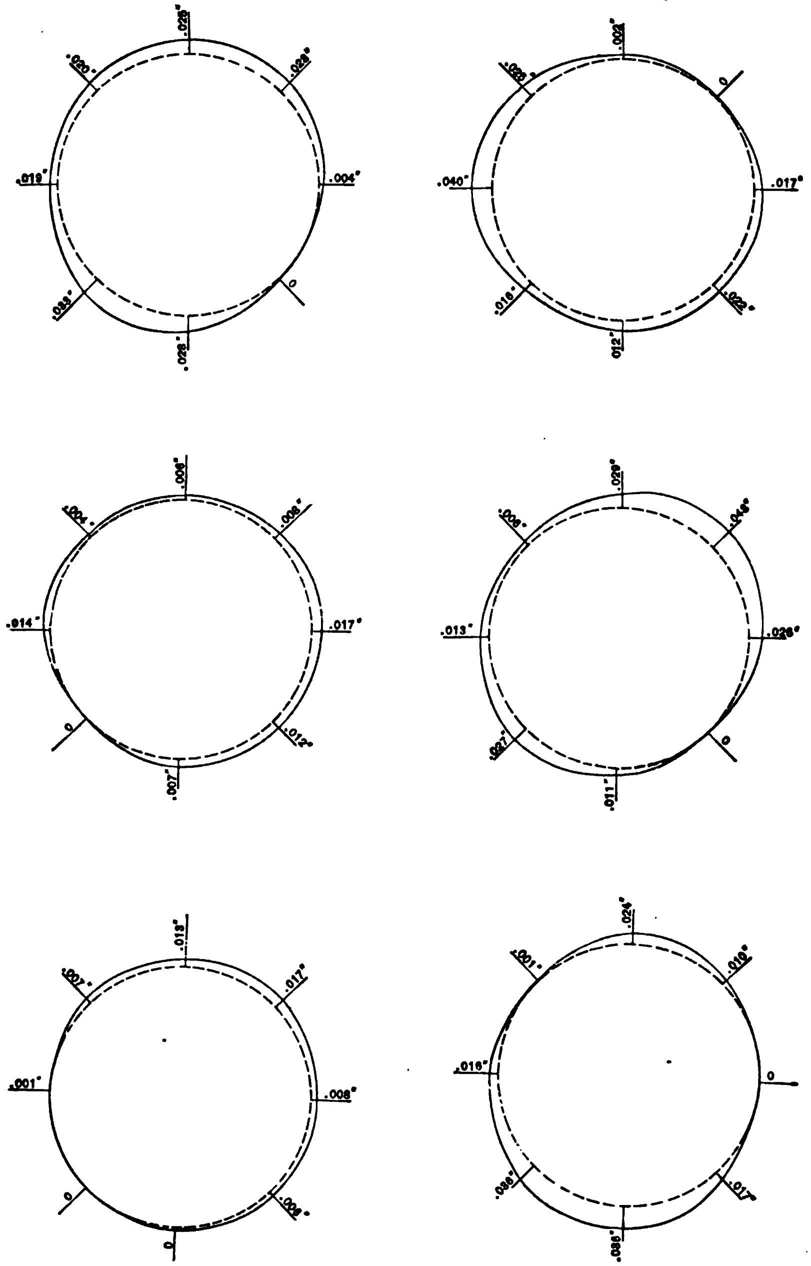


FIG. 26.—Continued.

tread. It is to be understood, however, that the figures given are the actual variations in the radii of the wheels from the datum circle.

Owing to the present imperfect state of our knowledge on this subject it would seem desirable to determine experimentally the exact effect of the blow delivered by a flat wheel on the rail.

Professor Benjamin* has designed an apparatus for such tests, which is shown in Fig. 27. The apparatus shown in the figure will permit of the continuous

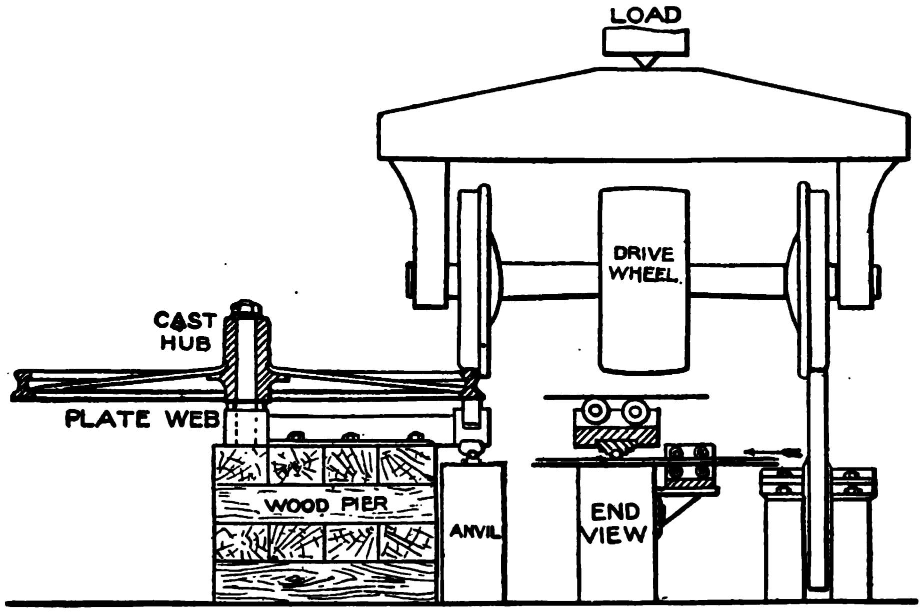


Fig. 27. — Apparatus for Measuring the Effect of a Flat Spot. (Benjamin.)

operation of one wheel upon one section of rail indefinitely and permit at the same time measurements of the effects of the blow. The truck is so supported that one wheel turns freely upon an idle pulley, while the other wheel on the same axle rests on a section of steel rail and in turning drives the latter by friction. The section of rail is bent to a circle, lying in a horizontal plane, and is firmly riveted and bolted to a supporting web, which is then fastened to a central hub of cast iron or steel. This hub turns freely on a vertical mandrel and is supported by a thrust bearing underneath. The rail and its attachments thus turn in a horizontal plane under the rotating car wheel. The portion of the rail immediately under the wheel is supported by friction rollers, which turn

* Paper presented at Meeting of Western Railway Club, November 17, 1908. See also discussion of Professor Benjamin's paper by H. H. Vaughan, American Engineer and Railroad Journal, December, 1908, and a further article by Professor Benjamin in the Railway Age Gazette, June 28, 1912, p. 1613.

freely in a steel box or yoke. This latter forms a portion of the main casting supporting the hub of the rail, and this casting is bolted to a wooden pier so as to have a certain amount of elasticity. On the lower side of this casting and directly beneath the point of contact between the wheel and the rail is a hardened steel hammer, or ball, resting on a strip of soft metal. The soft metal is supported on a heavy anvil of cast iron and is fed slowly beneath the hammer by friction rollers.

The truck being loaded with the desired amount of pig iron or other material, the wheels and their axles are rotated by means of a variable speed motor, and the energy of a blow delivered by a flat spot on the wheel is measured by the indentations of the strip of soft metal underneath the hammer. The amount of energy due to any given indentation can be readily measured by producing a similar indentation under a drop press. The curving of the rail in a horizontal direction is not sufficient to interfere with the action of the wheel and the energy of the blow is transmitted directly to the soft metal.

A subcommittee of the American Railway Engineering Association have made an attempt to measure the force of the blow caused by flat wheels under working conditions.

For this purpose an 80,000-pound capacity car was equipped with registering devices to measure the compression of the car springs and a pair of wheels with flat spots was placed in one of the trucks. The position of the flat wheels, springs, and the recording device is shown in Fig. 28. The recording device consisted of an apparatus for measuring the maximum deflection of the springs. The springs were calibrated, and it was found that a load of 32,500 pounds applied to a nest of four springs produced a compression of one inch.

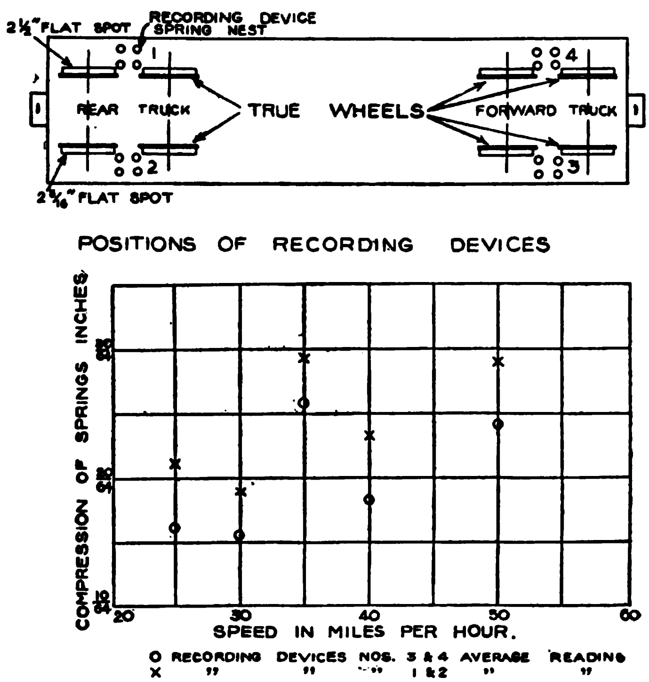


FIG. 28. — Diagram of Tests on Freight Car with Flat Wheels. (Am. Ry. Eng. Assn.)

The car was loaded with splice bars to its full capacity, the load being uniformly distributed. The train was then run for a short distance, brought to a stop, and the maximum deflection of the springs noted. Several different tests were made in this manner at different rates of speed, the results of which are shown by the diagram in Fig. 28.

The diagram shows quite uniformly for all of the tests a greater deflection of about a sixteenth of an inch for the trucks with flat wheels, corresponding to an increase in pressure on these trucks of from 1000 to 2000 pounds. The results would appear to indicate, then, that the flat wheels, either by increasing the oscillation of the car or for other reasons, cause an increase of pressure on the track.

On account of the small number of tests made and the fact that they were confined to one end of a car the results should not be regarded as conclusive. However, assuming that the effect of the flat spot in the wheel is to cause additional rocking of the vehicle, as the experiments would appear to indicate, it will be noted from article 7 that this force is already taken account of in the consideration of the excess pressure caused by the rocking of the locomotive on its springs.

9. Impact Tests

Professor Goss * experimented to determine the effect of the counterbalance pressure with the Purdue Test Locomotive. This engine is mounted with its drivers resting upon wheels of approximately the same diameter with the drivers, and when the drivers are turned by the engine the supporting wheels roll in contact with them, and the engine as a whole remains stationary. The engine was in complete horizontal balance and was counterbalanced heavier than it would be in ordinary road service, the main wheel being about 0.4 per cent and the rear wheel about 54.0 per cent more heavily balanced than is the usual practice.

A common annealed iron wire 0.037 inch in diameter was used and run under the drivers. Fig. 29 shows the effect of the drivers on the wire.

Wire I shows slight variation.

Wire II shows a jump of the wheel just after the counterbalance left the highest point, the lifting being retarded, probably due to inertia of the mass to be lifted.

* An Experimental Study of the Effect of the Counterbalance in Locomotive Drive-wheels upon the Pressure between Wheel and Rail. — Goss. Trans. Am. Soc. of Mech. Engrs., Vol. XVI, 1895, p. 305.

Wires III, IV, and V show the more marked lifting effects, due to increased speeds.

A light nick from a sharp chisel was made across the face of the wheel to serve as a reference mark, which left a clean-cut projection upon the wire. It was found at high speeds that the single nick across the face of the wheel leaves two projections upon the wire, usually about one-eighth of an inch apart. The contact between the wheel and the track would evidently appear, therefore, not to be continuous, but a succession of exceedingly rapid impacts. Professor Goss derived the following conclusions from his experiments:

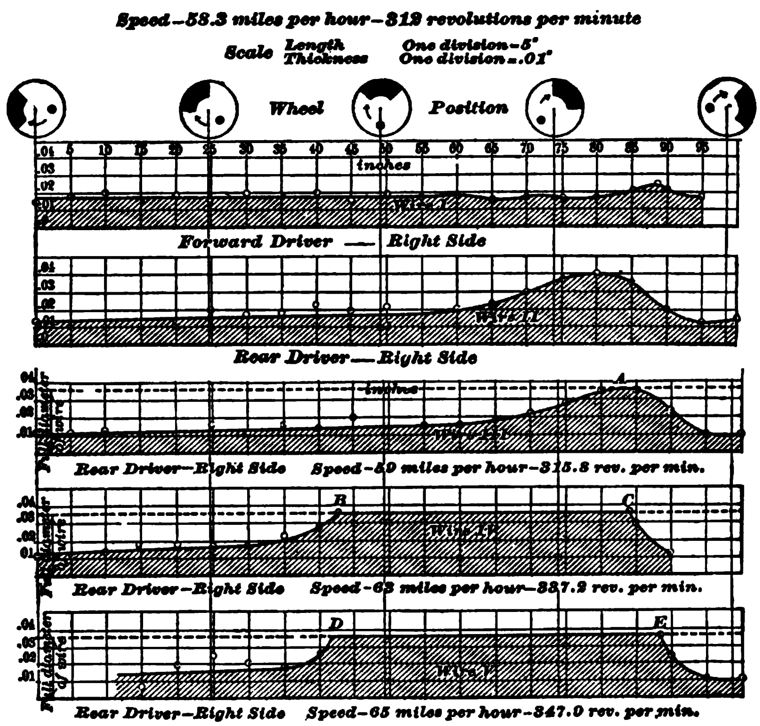


FIG. 29. — Wire Tests — Professor Goss.

(*a*) When a wheel is lifted through the action of its counterbalance, its rise is comparatively slow and its descent rapid. The maximum lift occurs after the counterbalance has passed its highest point.

(*b*) The rocking of the engine on its springs may assist or oppose the action of the counterbalance in lifting the wheel. It therefore constitutes a serious obstacle in the way of any study of the precise movement of the wheel.

(*c*) The contact of the moving wheel with the track is not continuous, even for those portions of the revolution when the pressure is greatest, but a rapid succession of impacts.

The question of impact has received a great deal of attention from bridge engineers. Recent work in this direction consists of a large number of experiments that were made on the Baltimore and Ohio Railroad by a subcommittee of the American Railway Engineering Association to determine the amount of impact in bridge members. The records of these tests were, unfortunately, burned in the Baltimore fire before they were put in permanent form. The experiments were continued by the Association under the direction of Professor Turneaure.

The importance of this subject was widely realized, and most of the large railroads in the country contributed towards a fund which enabled the work to be carried on with a great degree of thoroughness.

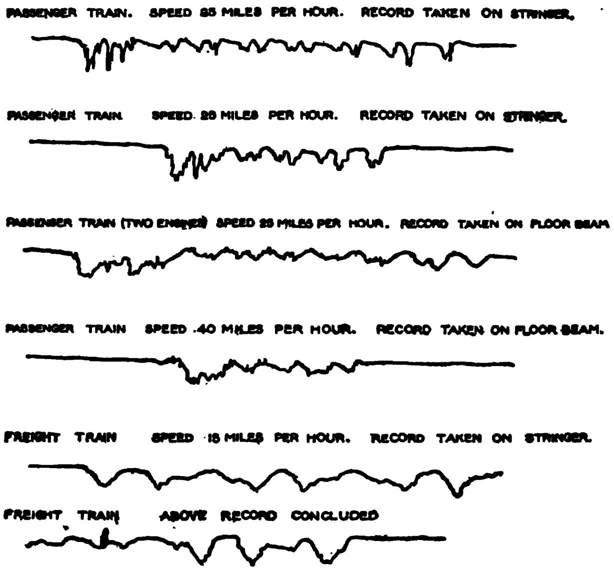


Fig. 30. — Deformation of Bridge Members under Passing Trains. (Am. Ry. Eng. Assn.)

Professor Turneaure's apparatus consisted of an autographic extensometer for recording the deformation of bridge members and multiplying that deformation by some factor like eighty or ninety and recording it on a moving strip of paper. On Fig. 30 are shown some of the records taken by one of these machines in 1906. It will be seen from an examination of the records that the effect of the different wheels can be readily traced in the diagrams.

During the season of 1907 * further work was done by the committee. The instruments used consisted of a deflectometer and eight extensometers. The deflectometer is the instrument described in Transactions A. S. C. E., Vol. XLI, June, 1899, p. 411. (Some Experiments on Bridges under moving Train-loads.) The instrument is itself attached to the bridge, while the connection with the ground below is made by means of a wire attached to a heavy weight resting upon the ground. The deflection is multiplied by two and

* Proceedings Am. Ry. Eng. and M. of W. Assn., 1908. Report of Committee on Iron and Steel Structures. Impact Tests.

recorded on a moving strip of paper. The extensometers are clamped to various members of a structure and record the extensions or compressions of the members over a length of about four feet. The ratio of multiplication of the extensometers is about 50.

Test trains were made up of a selected type of locomotive, followed generally by a sufficient number of loaded cars to cover the span. Longer trains were not used, for the reason that it was desired to secure speeds as high as possible, and also because many observations under the freight trains of the regular traffic showed that at the speeds practically attainable the impact effect was much less than with the shorter test train.

In carrying out the tests the train was headed in the more favorable direction for speed, and was moved back and forth over the structure at various rates of speed. Such speeds were selected as fairly to cover the range from about 20 miles per hour to the maximum attainable. A few movements were made at from 10 to 20 miles per hour. Little difference was noted in the results at various speeds below 15 miles per hour, and in general the results at 10 miles per hour may be considered as practically equal to static stresses.

The speed of the train was determined by the use of stop watches and signals by observers stationed at the ends of a 500-foot base line. The locomotive was generally working when crossing the span, but in some cases was not. Differences in this respect caused no noticeable differences in results, so far as the field observers were able to judge, although this point was considered mainly with respect to the higher speeds. Each test was given a serial number, and all records obtained for that test were given the same number.

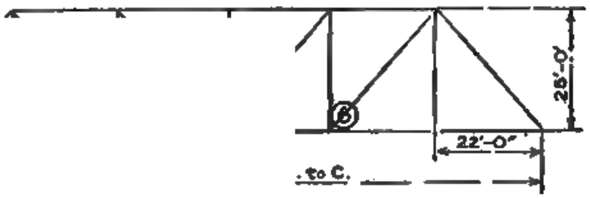
TABLE XII. — CALIBRATION TABLE, IMPACT TESTS ON BRIDGES.

Instrument Number.	Lever Multiplication.	Value of 1 inch Ordinate, $E=30,000,000$, $L=48$ inches.	Speed of Paper, Inches per Second.
Deflection	2	....	....
1	55.4	11,300	0.642
2	....	....	....
3	48.4	12,900	0.547
4	53.7	11,600	0.613
5	51.7	12,100	0.523
6	54.2	11,500	0.703
7	54.5	11,500	0.583
8	54.3	11,500	0.602

Table XII contains calibration data of the instruments and the approximate speed of movement of the record paper. Table XIII contains detailed data of one of the tests. This sheet represents the work of one day on one structure,

TABLE XIII.—IMPACT TESTS ON BRIDGES.

ENGINE No 1919. CB & Q 39393 WAY CAR BRIDGE No 9 RECORDS 265-301 SEPT. 9, 1907. ENGINE No 1919



Record No.	Speed, M.p.h.	Counter-balance.	Max.	Amp.	Rem.	Max.	Amp.	Peak.	Rem.	Max.	Amp.	Peak.	Rem.	Max.	Amp.	Peak.	Rem.
265	7	6 02 S.	150	5						60				49			
6	9	6 02 S.	153	9		30								50			
7	20	6 52 S.	150	.		25				65				52			
8	20	6 77 S.	148			22				70	15			53			
9	26	7 37 S.	150	12		24				72				57			
270	26	7 72 S.	150	15		24				72				60			
1	30	8 37 S.	157	25		25				67				60			
2	31	8 67 S.	158	30		25				69				61			
3	36	9 97 S.	180	55		31				63				66	30		
4	33	7 77 N.	166	45		25				66				67			
275	39	6 37 N.	183	80		31				70				63			
6	37	5 62 N.	181	75		30				59				71	40		
7	39	4 42 N.	168	80		33				55				62	30		
8	39	3 57 N.	183	70		35				65				67	35		
9	45	3.27 N.	162	40		29				101	70			70	50		
280	47	0 97 N.	158	40		28				109	70			73	50		
1	33	1 87 N.	159	40		25				61				70	45		
2	35	1 07 N.	163	50		28				73	30			76	45		
3	35	0 22 N.	170	55		29				72	40			68	40		
4	35	0 33 S.	165	50		28				72	40			70			
285	34	0 43 S.	174	65		30				85	50			78	40		
6	40	1 53 S.	170	60		35				88	60			70	40		
7	40	...	172	70		39				83	60			68	30		
8	40	4 37 S.	170	70		46				80	45			65	30		
9	46	5 72 S.	150	40		46				...				62	40		
290	43	6 22 S.	152	40		39								63	40		
1	10	4 87 S.	138			30				56				52			
2	11	4,87 S.	139			29				56				50			
3	16	5 07 S.	140	10		33				61				52			
4	15	3 62 S.	140	6		30				61				53			
295	25	4 27 S.	143	15		31				63				52			
6	20	4 07 S.	139	6		33				67	15			58			
7	25	4 57 S.	146	15		35				62				57			
8	27	5 22 S.	143	20		34				73				51			
9	46	6 07 S.	152	50		39	10			97	50			60	40		
300	40	7 42 S.	165	70		40	10			70				58	20		
301	48	8 02 S.	146	40		46	12			90				60			

Record No.	Max.	Amp.	Peak.	Rem.	Max.	Amp.	Peak.	Rem.	Max.	Amp.	Peak.	Rem.	7 Stringer, Second Panel, North Flange. $L=4.01$. Max.	Amp.	Peak.	Rem.	8 Stringer, Third Panel, North Flange. $L=4.05$. Max.	Amp.	Peak.	Rem.
265	66				43				80				56				50			
6	67				42								54				54			
7	71				47				78				59				61			
8	75				48				80				61				50			
9	79				42				78				58				51			
270	81								80				56				51	15		
1	79				48				86				61				51			
2	76				51	6			90	15			56				55			
3	80				60	15			105	50			60				61			
4	82				58	12							60				56			
275	88				59	20			100	40			70				65	30		
6	78				63	20			100	40			61				52			
7	67				66	25			103	50			68				61			
8	89				60	20			102	40			69				60			
9	88				50	18			88	20			40			I	79			
280	88				55				86				50		77	I	62			
1	71				48				95	30			60				53			
2	78				50				90	30			64				53			
3	81				52	16			98	35			70				60			
4	81				50	16			95	30			75				60			
285	88				59	20			102	40			78				70			
6	82				59	20			98	30			78				76			
7	90				61	25			90	30			70			I	70			
8	84				58	25			100	35			72				65			
9	96				52	18			82	20			45				69			
290	90				48	15			82	15			50				71			
1	69				40				75				57				50			
2	69				40				73				55				50			
3	71				43				76				50				52			
4	70								76				59				55			
295	71								80	8			58				50			
6	73				40				79				58				50			
7	74				44				88				55				52			
8	82				45				86	10			53				50			
9	91				45	20			82				50				71			
300	86				59	25			93	40			60			I	60			
301	88								80				52			I	50			

and with a particular locomotive and train. At the top of the sheet are given the weights of test train, and a diagram of the bridge, showing the general location of the instruments by number. The table then gives, first, the number of the test, then the speed in miles per hour, then the position of the counterbalance, as will be described more fully later. Then follow the data relating to the deflection and measurements of the various extensometers from Nos. 1 to 8. The location of each instrument is given immediately below the number.

In the column headed "Maximum" is given generally the value of the maximum ordinate of the diagram resulting from the test, expressed in hundredths of inches. An exception to this is where there was obviously considerable instrumental vibration, in which case an effort was made in scaling the diagrams to eliminate this instrumental effect. This could be done in many cases quite satisfactorily, but not in other cases, and all such records are open to more or less doubt.

In the column marked "Amplitude" is given the amplitude of the vibrations in the diagrams where such vibration is apparently due to the structure and is not instrumental vibration. Vibrations may be due in general to three causes: (*a*) vibrations of the structure as a whole, as shown most clearly in the deflection diagrams and the chord or flange stresses; (*b*) vibrations of individual members, especially eyebars, and (*c*) instrumental vibrations.

Other marked variations in the diagrams occur in such members as stringers, floor beams, and hip verticals. It can only be stated at present that it is generally possible to distinguish instrumental vibrations from others because of their much greater rapidity. It may be said, however, that in most of the diagrams obtained the instrumental vibrations are not serious.

In the column marked "Peak" are given the measured ordinates to the highest points of the curves, including instrumental vibration. The excess of this value over the "Maximum" shows the extent of the instrumental vibration as estimated. In many cases this is small, but in many cases also it is large. In some cases it is so excessive that no attempt has been made to measure the records. The deflectometer gave no trouble in this respect.

In the column headed "Remarks" are noted various remarks by the use of letters: "I" signifies instrumental vibration.

Returning to column three, headed "Counterbalance": In the later tests the position of the counterbalance was determined with reference to some panel point of the bridge. This was done by inserting an index made of $\frac{1}{4}$-inch steel into the rim of one of the drivers, exactly opposite the counterbalance. Then, alongside the rail was placed a 2- by 4-inch strip, on which was placed a ridge

of clay or putty at such a height as to be indented by the index as it passed along. The position of the indentation is noted in feet north or south of the point of reference, which point of reference is shown on the truss diagram by the letter "C."

During the seasons of 1908 and 1909 the experiments were continued, and very complete data gathered of a number of bridges under different conditions of loading.*

The experiments obtained in this series of tests indicate that with track and rolling stock in good condition the main cause of impact is the unbalanced condition of the drivers of the ordinary locomotives. The great importance of unbalanced drivers is well brought out by a comparison of the results of comparative tests with the ordinary locomotive and the balanced compound and electric locomotive. The impact caused by balanced compound and electric locomotives was very small.

While it is interesting to study the effect of the impact in the different members of a bridge in a consideration of the stresses in the rail, it is doubtful whether the two cases are sufficiently alike to afford anything more than a general comparison.

In considering the impact stresses in the rail the effect of the inertia of the track must be borne in mind.

If we examine what takes place in the track under the impact of the wheel it is seen that there is a force F acting between the wheel and the rail. When impact occurs this force is increased by a force F' which produces a change in the relative velocities of the wheel and the track, but on account of the nature of the track the change in its velocity is almost impossible to determine.

The average value of this force F' is exactly equal to the change in momentum produced by its action divided by the time required to produce this change

or
$$F' = m\frac{(v - v_1)}{t - t'},$$
where
$$m = \text{mass},$$
$$v = \text{velocity},$$
$$t = \text{time}.$$

It will be observed that the interval of time $t - t'$ during which the impact acts is very small, and is not sufficient to allow the force F' to depress the track at high speeds, with the result that the force F' is overcome mainly by the resistance of the rail to compression. The heavier and harder the rail, there-

* Proceedings Am. Ry. Eng. and M. of W. Assn., 1911, Vol. 12, Part 3, p. 12. Report of Subcommittee on Impact.

fore, the greater is this force F', other things being equal. Indeed it is quite possible that it may at times exceed the crushing strength of the rail on its upper surface.

A division of the forces acting on the wheel into those which produce local strains in the running surface of the head and the forces which tend to set up bending stresses in the rail is difficult to determine; probably the effect in producing bending stresses of all the forces except the static load on the wheel and the centrifugal force described in Article 6 are considerably lessened owing to the inertia of the track.

This especially applies to the pressure exerted by the springs of the locomotive when the engine is rocking. If the full effect of the compression of the springs was realized the pressure might well be twice what has been taken.

This was illustrated in the impact tests on bridges when the excess pressure, caused by the counterbalance, tended to produce well-defined strains, and at or near the critical speeds would set up vibrations in the bridge itself, while the impact from the rocking of the locomotive on its springs apparently caused a much less serious effect.

10. The Dynamic Augment of the Wheel Load

While we have examined the various causes of the increase in wheel pressure when the locomotive is running, it is still necessary to consider the effect of the velocity of the wheel load.

Assuming the track perfectly smooth, the wheel without imperfections and all of the rotating parts perfectly balanced, the effect of a load moving over the track at a high rate of speed depends wholly upon the vertical curvature of the track and the effect which this curvature has upon the path over which the center of gravity of the load travels.

In the case of a bridge, if we assume the track originally straight and absolutely rigid, the amount of impact or centrifugal force resulting from the deflection of the structure can be approximately determined on theoretical grounds. Such an analysis has been made by Dr. H. Zimmermann for the case of a single rolling load, and a formula which is very closely approximate to his exact formula is as follows:

$$F = P \frac{1}{\dfrac{gl^2}{16\,v^2 d} - 3},$$

in which F = centrifugal force, P = weight of rolling load, v = velocity in feet per second, d = deflection of structure, and l = span length. If, for example,

$d = \frac{1}{2400}$ of span length and $v = 90$ feet per second (about 60 miles per hour), we have

$$F = P\frac{1}{0.595\,l - 3},$$

a formula which is practically exact for spans greater than 15 feet. For a 25-foot span this gives 8.7 per cent impact, and for a 50-foot span 3.7 per cent. For a 100-foot span the value would be 1.7 per cent.

With the yielding supports under the rail the center of gravity of the load tends to travel along a straight line (assuming the track to be perfectly uniform). It seems therefore probable that the dynamic stress in the rail is not increased by any appreciable amount by the velocity of the wheel load, and the maximum pressure to be used in calculating the stress in the rail can be taken to be made up of the static wheel load, the excess pressure due to the counterbalance and angularity of the main rod, the pressure due to the wheel passing over irregularities in the surface of the track, and the pressure caused by the rocking of the engine on its springs.

The imposed pressure due to the angularity of the main rod and the excess balance is given in Table XIV.

TABLE XIV. — MAXIMUM DYNAMIC PRESSURE, IN POUNDS, DUE TO ANGULARITY OF MAIN ROD AND EXCESS BALANCE, FOR SPEEDS UP TO 60 MILES PER HOUR

Type.	Weight on Axle.		Excess Pressure Due to Angularity of Main Rod and Excess Counter-balance. (One Side Only.)	
	Main Driver.	Front or Back Drivers.	Main Driver.	Front or Back Drivers.
4-4-2	55,000	52,000	12,000	9,000
4-6-2	60,000	56,000	10,000	7,000
4-6-0	55,000	52,000	11,000	10,000
2-6-0	54,000	53,000	15,000	11,000
2-8-0	54,000	50,000	14,000	9,000

This pressure is not a direct function of the wheel load and should be expressed in pounds for each class of locomotive.

The excess pressure for the freight locomotive, types 2-6-0 and 2-8-0, is noticeably greater than is that of the passenger locomotive for the high speeds given in Table XIV. Inasmuch as the engines in freight service are not called upon for as high speed as in the passenger service, the excess pressure at 40 miles per hour may be taken as the maximum for the engines of this class. The greatest pressure occurs with the Mogul locomotive, type 2-6-0, and is 10,000 pounds for the main driver and 5000 pounds for the front and rear drivers.

The extra pressure due to irregularities in the track is dependent on the weight on the wheel and may be expressed in per cent of the wheel load, and is $\frac{4000}{30,000}$ = 13 per cent of the weight on the driver.

The pressure due to the rocking of the engine on its springs is likewise a function of the wheel load, and is 13 per cent of the load on the driver.

Dr. P. H. Dudley has observed that the drawbar pull and the tender on stiff rails can become important factors in distributing the effect of the expended tractive power to a longer portion of the track than that occupied by the driving wheel base.

The distribution of the expended tractive effort through the drawbar pull may be extended in 6-inch, 100-pound rails to all of the wheels under the locomotive. In the 80-pound rail this reduces to about two-thirds of the length of the total wheel base of the locomotive.

Two stremmatograph tests were made for the purpose of tracing the distribution of the stresses due to the expended tractive power of the locomotive when drawing its train. The first test was made with the engine light, backing over the stremmatograph, and then in a few moments coming forward. The second test was made with the same engine drawing its train. It indicated that the unit fiber stresses are increased under all of the wheels of the locomotive, and also the bending moments.

The effect of the expended tractive effort through the drawbar pull and the stiff rails was distributed for the entire length of the wheel base of the locomotive, instead of being restricted to that of the driving wheels. The total wheel effects under the light locomotive for one rail were 1,368,706 inch-pounds, and 1,864,363 inch-pounds when drawing the train, an increase of nearly 500,000 inch-pounds, or 1,000,000 inch-pounds, practically, for both rails.

It is evident that this increase in pressure on the rail is allowed for by the dynamic augment to the spring-borne load of the locomotive, and we may now prepare Table XV, giving the dynamic augment to be added to the static wheel load.

TABLE XVa. — DYNAMIC AUGMENT TO BE ADDED TO THE STATIC WHEEL LOAD WHEN THE LATTER IS 25,000 POUNDS OR OVER

Class.	Dynamic Augment.		
	Pounds.		Per cent.
	Main Drivers.	Front and Back Drivers.	
	1	2	3
Passenger.......	12,000	9,000	26
Freight..........	10,000	5,000	26

NOTE. — The dynamic augment as given in pounds in columns 1 or 2 should be added to the per cent of the wheel load given in column 3, to give the total dynamic augment for the drivers. Column 3 only should be used for the truck wheels.

TABLE XVb. — DYNAMIC AUGMENT TO BE ADDED TO THE STATIC WHEEL LOAD WHEN THE LATTER IS LESS THAN 25,000 POUNDS

Class.	Dynamic Augment.		
	Main Drivers.	Front and Back Drivers.	Truck Wheels.
	Per cent	Per cent	Per cent
Passenger........	75	60	26
Freight..........	66	45	26

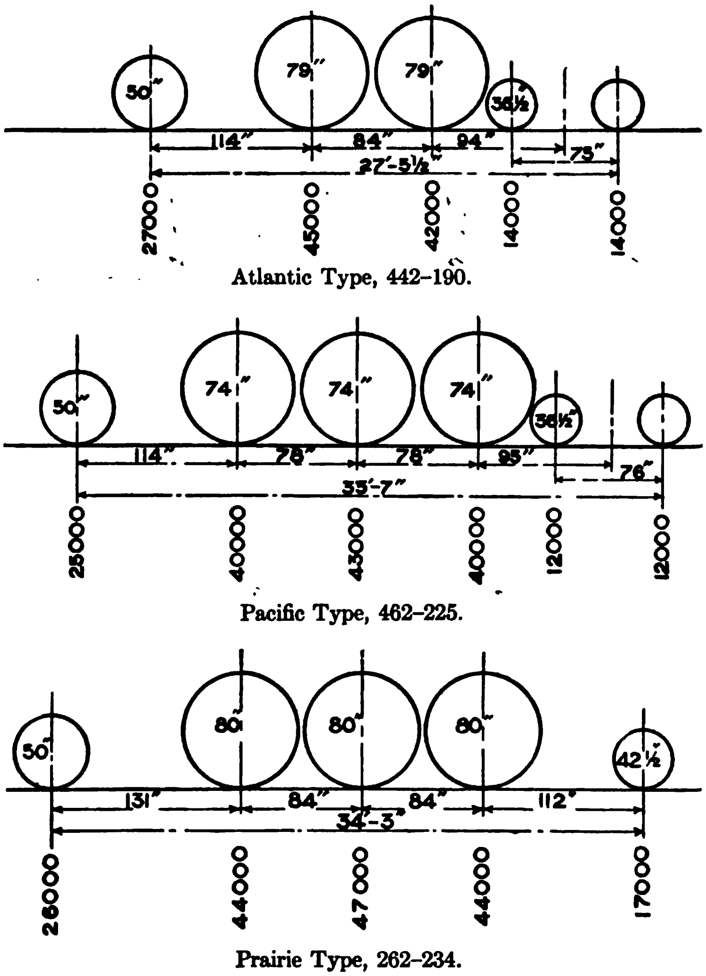


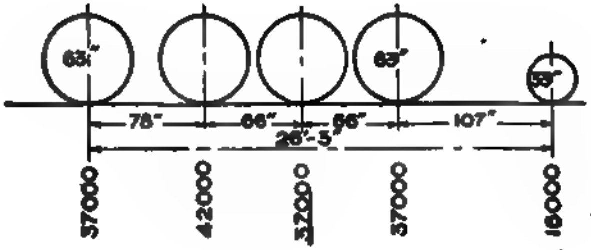
FIG. 31. — Dynamic Wheel Loads of Typical Passenger Steam Locomotives.

See Plate XX for static loads and Table XV for relation between static and dynamic loading.

Note. — Total weight on drivers assumed to be equally divided between the driving axles; if the main wheel is more heavily loaded the dynamic pressure will be increased accordingly.

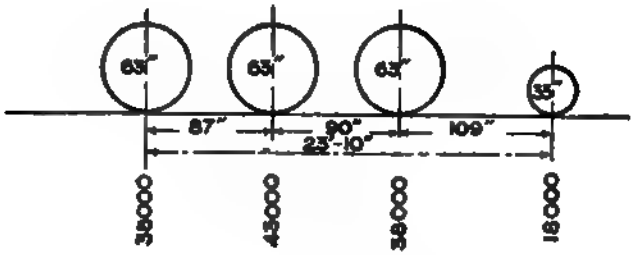
By referring to Figs. 6 and 7 it is seen that the excess pressure, caused by the angularity of the main rod and counterbalance, is less in amount for these lighter engines. Table XVb shows the dynamic augment of engines having wheel loads less than 25,000 pounds.

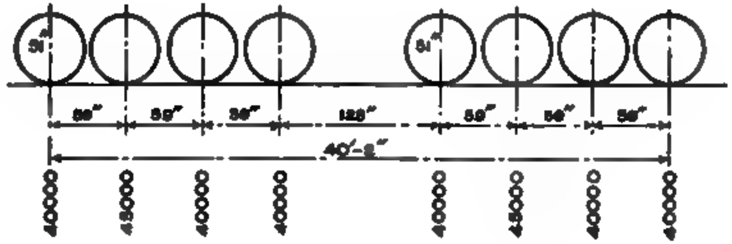
We may now proceed to construct typical load diagrams for the different classes of locomotives. Plates XX and XXI give the principal dimensions of each type of engine under discussion, from which, with the aid of Table XV, the load diagrams given in Fig. 31 and Fig. 32 have been prepared.



Ten-wheel Type, 460-194.

Consolidation Type, 280-226.





Mogul Type, 260-187.

Articulated Type, 0880-445.

FIG. 32. — Dynamic Wheel Loads of Typical Freight Steam Locomotives.

See Plate XXI for static loads and Table XV for relation between static and dynamic loading.

Note. — Total weight on drivers assumed to be equally divided between the driving axles; if the main wheel is more heavily loaded the dynamic pressure will be increased accordingly. It is very difficult to weigh the loads on separate axles with any degree of accuracy, as the weights vary according to whether the engine is run on the scale forwards or backwards and the tractive effort even changes the position of the equalizing levers so that more weight is thrown on one axle at a time than another.

11. Electric Locomotives

* In dealing with the electric locomotive the question of the excess balance necessary to counteract the reciprocating parts can be entirely neglected, and these machines, when properly constructed, would appear to have a more favorable action on the track than is the case with a steam engine of the same capacity.

The low center of gravity possessed by the earlier locomotives of this type imposed, under certain conditions, a very severe duty on the rail. † In order to bring out the facts experimentally, the Pennsylvania Railroad Company, who were about to design locomotives for their tunnel entrance into New York City, constructed a special test track with apparatus for measuring side pressures upon the rail; they built sample locomotives of different designs and instituted a series of tests of electric and steam locomotives to determine their relative riding qualities at speed.

It was found that all types of locomotives were practically steady at speeds under 40 miles per hour, but that above this speed marked differences appeared; that the steadiest riding machines were those with high center of gravity and with long and unsymmetrical wheel base. In other words, that the nearer steam-locomotive design is approached in wheel arrangement, distribution of weight, height of center of gravity, and ratio of spring-borne to under-spring weight, the less the side pressures registered on the rail head.

TABLE XVI. — ELECTRIC AND STEAM LOCOMOTIVES, COMPARISON OF WEIGHTS AND CENTERS OF GRAVITY. (Gibbs.)

	Electric.				Steam.	
Type	0-4-4-0	4-4-4-4	4-4-4-4	2-4-4-2	2-4-4-2	4-4-0
Railroad	Pennsylvania.	Pennsylvania.	Pennsylvania.	N. Y., N. H. & H.	Pennsylvania.	Pennsylvania.
Service	Experimental.	Experimental.	N. Y. Tunnel.	Main Line.	Main Line.	Main Line.
Total weight of locomotive, running order in pounds	195,140	304,000	332,000	202,000	176,600	138,000
Height, center gravity, complete loco, from rail, inches	42.5	55	63.75	53	73	63
Per cent of weight of running gear below springs to total weight	50	46.3	16.7*	37.4	22.7	22.7
Heights of center of gravity of running gear from rail, inches	28	33.5	30.2*	30	33	29

* Does not include motors as they are mounted in cab.

Table XVI presents a comparison of weights and centers of gravity of modern electric locomotives and steam locomotives. Fig. 33 shows the Detroit River Tunnel Company's locomotive.

* See the Railroad Age Gazette, Vol. XLVII, 1909, pp. 271, 319, 537, 881, and the Railway Age Gazette, Vol. XLVII, 1910, p. 829, for descriptions of electric locomotives given in this article.

† Electric Traction by George Gibbs, report presented before the International Railway Congress, July, 1910. See also a very complete article "The Electrification of Railways" by George Westinghouse. Appendix No. 2. Data on Electric Locomotives of American Design, pp. 970–979. Trans. Am. Soc. of Mech. Engrs., 1910. Vol. 32.

Fig. 33. — Detroit River Tunnel Company's Locomotive. (Railway Age Gazette.)

Fig. 34 illustrates the type of the Pennsylvania Electric locomotives which are used for handling the Pennsylvania Railroad trains into the New York station.

Fig. 34. — Pennsylvania Electric Locomotive in Use in the New York Tunnels. (Railway Age Gazette.)

This locomotive incorporates many novel features in electric-locomotive design, and is the result of several years' coöperative development between the Pennsylvania Railroad Company and the Westinghouse Electric and Manufacturing Company. It is distinctively a high-powered machine, built for high speed operation.

In wheel arrangement, weight distribution, trucks and general character of the running gear, it is the practical equivalent of two American type locomotives coupled permanently back to back.

The connecting rods are all rotating links between rotating elements, and are thus perfectly counterbalanced for all speeds.

The employment of this transmission permits the mounting of the motors upon the frame, secures their spring support, and, in common with the rest of the locomotive, the center of gravity at approximately the same height above the rails, found desirable in the best high-speed steam experience. The same freedom of motion in the wheels and axles that is

characteristic of the present steam locomotive is also obviously secured. It will be seen from Fig. 35 that the locomotive is an articulated machine and that each half carries its own motor and has four driving wheels, 68 inches

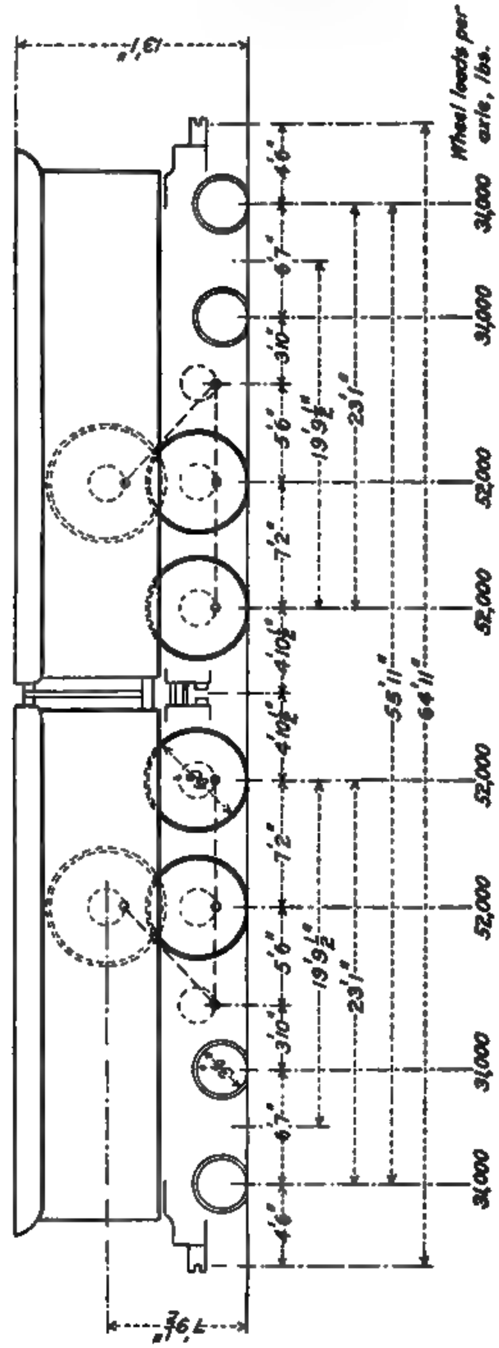


FIG. 35.—Details Pennsylvania Electric Locomotive. (Railway Age Gazette.)

in diameter, and one four-wheel swing bolster swivel truck with 36-inch wheels. In these locomotives the variable pressure of the unbalanced piston of the steam locomotive is replaced by the constant torque and constant rotating effort of the drive wheels, and the pull upon the drawbar is thereby constant and uniform. It might to the casual observer appear that by this arrangement of driving a return has been made to steam locomotive practice as regards counterbalancing difficulties, but it will, upon examination, be seen that nothing of the kind is true. There are no questions of unbalanced reciprocating weights involved, and all weights are revolving ones and directly counterbalanced.

In Table XVII is given the general characteristics of the electric locomotives of this country.

In determining the dynamic augment of the wheel load in the case of the electric locomotive, the effect of the counterbalance, which plays such an important part in the pressure of the driver of the steam locomotive, can be entirely neglected. The other causes remain approximately the same, and by referring to Table XV (column 3), it is seen that the dynamic augment amounts to 26 per cent of the wheel load. Fig. 36 gives the load diagrams of electric locomotives based upon this assumption.

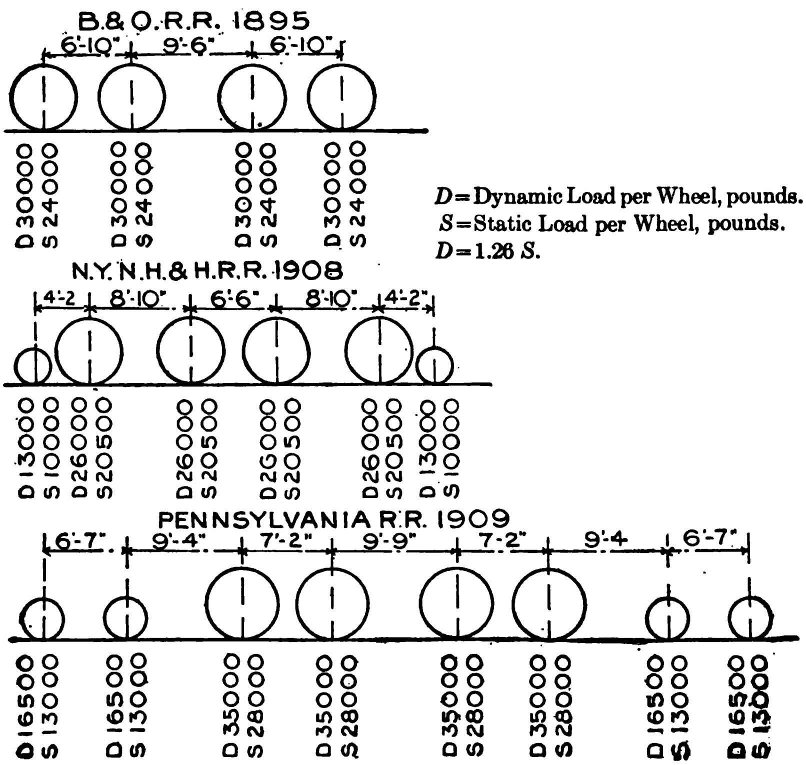


FIG. 36.—Typical Load Diagrams for Electric Locomotives.

TABLE XVII.—GENERAL CHARACTERISTICS OF ELECTRIC LOCOMOTIVES. (GIBBS.)

	Baltimore & Ohio Railroad.		New York Central & Hudson River R.R.		Pennsylvania Railroad.		
	Passenger.	Freight.	Original.	Revised.	Experimental.	Experimental.	Passenger.
General:							
Builder: Mechanical	American Loco. Co.	American Loco. Co.	American Loco. Co.	American Loco. Co.	Pennsylvania R.R.	Baldwin Loco. Wks.	Pennsylvania R.R.
Builder: Electrical	General Elec. Co.	General Elec. Co.	General Elec. Co.	General Elec. Co.	Westinghouse Co.	Westinghouse Co.	Westinghouse Co.
Date built	1895.	1903.	1906.	1908.	1905.	1907.	1909.
Type	0-4-4-0	0-8-0	2-8-2	4-8-4	0-4-4-0	4-4-4-4	4-4-4-4
Number of driving wheels	8	8	8	8	8	8	8
Number of truck wheels			4	8		8	8
Number of motors	4-DC.	4-DC.	4-DC.	4-DC.	4-DC.	4-DC. single-phase	2-DC.
Dimensions:							
Length over couplers	35 feet 0 inches	29 feet 0 inches	37 feet 0 inches	43 feet 0 inches	36 feet 5 inches	65 feet 8 inches	64 feet 11 inches
Width of cab	9 " 5 "	9 " 5 "	10 " 0 "	10 " 0 "	10 " 2 "	10 " 0 "	10 " 0 "
Height, rail to top of roof	14 " 3 "	13 " 8 "	14 " 4 "	13 " 9 "	13 " 1 inch	13 " 1 inch	13 " 1 inch
Driving wheel base	23 " 2 "	14 " 7 "	13 " 0 "	13 " 0 "	26 " 1 "	30 " 0 "	24 " 1 "
Truck wheel base	6 " 10 "			6 " 0 "	8 " 6 inches	6 " 2 inches	6 " 7 inches
Rigid wheel base	6 " 10 "	14 " 7 "	13 " 0 "	13 " 0 "	8 " 6 "	7 " 6 "	7 " 2 "
Total wheel base	23 " 2 "	14 " 7 "	27 " 0 "	36 " 0 "	26 " 1 inch	56 " 2 "	55 " 11 "
Diameter of driving wheels	62 inches	42 inches	44 inches	44 inches	56 inches	72 inches	68 inches
Diameter of truck wheels			36 inches	36 inches		36 inches	36 inches
Weights:							
Per driving axle, in pounds	48,125	40,000	33,500	35,500	48,785	54,900	55,800
Per truck axle, in pounds			28,000	22,000		21,150	26,400
Total, in pounds	192,600	160,000	190,000	230,000	195,140	304,000	328,800
Per foot of wheel base in pounds	8,340	11,000	7,040	6,400	7,500	5,430	5,870
Center of gravity of locomotives	43.2 inches	40.5 inches	44.4 inches	40.0 inches	42.5 inches	55.0 inches	63.75 inches
Speed:							
Approximate with full load on level, miles per hour	20	10	60	60	45	60	60

TABLE XVII.—GENERAL CHARACTERISTICS OF ELECTRIC LOCOMOTIVES. (GIBBS.)—*Continued*

	New York, New Haven & Hartford R.R.		Spokane & Inland Railroad.		Grand Trunk, Sarnia Tunnel.	Great Northern Railway.	Michigan Central Detroit R. Tunnel.
	Original.	Revised.	Freight.	Freight.	Passenger and Freight.	Freight.	Freight.
General:							
Builder: Mechanical	Baldwin Loco. Wks.	Baldwin Loco. Wks.	Baldwin Loco. Wks.	Baldwin Loco. Wks.	Baldwin Loco. Wks.	American Loco. Co.	American Loco. Co.
Builder Electrical	Westinghouse Co.	Westinghouse Co.	Westinghouse Co.	Westinghouse Co.	Westinghouse Co.	General Elec. Co.	General Elec. Co.
Date built	1906.	1908.	1906.	1907.	1907.	1908.	1909.
Type	0-4-4-0	2-4-4-2	0-4-4-0	0-4-4-0	0-6-0	0-4-4-0	0-4-4-0
Number of driving wheels	8	8	8	8	6	8	8
Number of truck wheels		4				8	8
Number of motors	4-AC. single-phase	4-AC. single-phase	4-AC. single-phase	4-AC. single-phase	3-AC. single-phase	4-AC. three-phase	4-DC.
Dimensions:							
Length over couplers	37 feet 7 inches	37 feet 7 inches	32 feet 1 inch	38 feet 3 inches	29 feet 4 inches	44 feet 2 inches	39 feet 6 inches
Width of cab	9 " 7 "	9 " 7 "	9 " 6 inches	9 " 6 "	10 " 2 "	10 " 0 "	10 " 0 "
Height, rail to top of roof	12 " 2 "	12 " 2 "	11 " 9 "	12 " 2 "	13 " 0 "	14 " 2 "	12 " 4 "
Driving wheel base	22 " 6 "	22 " 6 "	21 " 1 inch	24 " 10 "	16 " 0 "	31 " 9 "	27 " 6 "
Truck wheel base	8 " 0 "	8 " 0 "	7 " 4 inches	9 " 6 "		11 " 0 "	9 " 6 "
Rigid wheel base	8 " 0 "	8 " 0 "	7 " 4 "	9 " 6 "	16 " 0 "	11 " 0 "	9 " 6 "
Total wheel base	22 " 6 "	30 " 10 "	21 " 1 inch	24 " 10 "	16 " 0 "	31 " 9 "	27 " 6 "
Diameter of driving wheels	62 inches	62 inches	38 inches	50 inches	62 inches	60 inches	48 inches
Diameter of truck wheels		33 inches					
in pounds	48,000	40,500	25,070	38,250	42,200–47,000	57,500	50,000
pounds		20,000					
	192,000	202,000	100,280	145,000	131,400	230,000	200,000
base, in pounds	8,540	6,530	4,750	5,830	8,200	7,220	7,280
of locomotives	53.0 inches				51 inches	60 inches	42.5 inches
Speed:							
Approximate with full load on level, miles per hour	60	60	25	15	35	15	35

12. Cars

In dealing with the pressure of the wheels of cars it will be noted that the dynamic load is much less than is the case with the heavy steam locomotive. Here the only dynamic effect caused by the rapidly moving wheel is that of the rocking of the car on its springs, the irregularities of the track and lack of roundness of the wheel.

Fig. 28 gives a convenient means for estimating the excess pressure caused by the rocking of the car. It will be noted from the figure that the maximum dynamic pressure corresponds to a depression of the nest of springs of about $\frac{5}{16}$ inch at a speed of 50 miles per hour, or, as the springs are capable of resisting a slowly applied load of 32,500 pounds for a depression of 1 inch, the dynamic load at 50 miles per hour for the two wheels supported by the nest of springs is probably about 5000 pounds, or 2500 pounds for each wheel greater than the static load.

Fig. 37. — Box Car. Capacity 100,000 lbs. Weight 48,000 lbs. Length 40 ft.

An allowance of 10,000 pounds per wheel would appear to be ample to cover higher speeds obtained and heavier cars than that used in the test to which this figure refers, as well as any increase in pressure caused by irregularities in equipment. With lighter loads the dynamic augment may be decreased, and for wheel loads less than 15,000 pounds it has been taken as 0.7 of the static load.

Figs. 37 to 41 * illustrate types of freight cars and Figs. 42 to 46 * passenger cars. It will be seen that the freight cars use a four-wheel truck, each wheel of which sustains about 20,000 pounds for 100,000-pound capacity cars when loaded to their full capacity. The minimum spacing of wheels used under 100,000-pound capacity cars is 5 feet 6 inches. Cars in passenger service as seen from the figures use four-wheel trucks and also six-wheel trucks. The wheel

* Figs. 37 to 46 have been taken from the Car Builders Dictionary.

spacing of the four-wheel trucks is 8 feet and for those having six wheels, 5 feet 3 inches.

The increase in weight in American passenger equipment in recent years has been very great. Steel coaches with wood inside finish used by one of the Chicago lines weigh 139,000 pounds. New buffet library cars for another

FIG. 38. — Flat Car, Pressed Steel Underframe. Capacity 100,000 lbs. Weight 38,000 lbs.

western line weigh 153,000 pounds. In the design for new sleepers for the Pennsylvania it is difficult to limit the weight to 160,000 pounds, and 75 to 80 tons may be taken as the weight of modern sleeping cars. The 70-foot steel coaches, which are being built in large numbers, are so heavy that it is necessary to use six-wheel trucks under them, and these alone weigh over 40,000 pounds for two trucks.*

FIG. 39. — Gondola Car. Wooden Body. Pressed Steel Underframe. Capacity 100,000 lbs. Weight 44,500 lbs.

The proposed use of 80-ton freight cars with four-wheel trucks for special service † suggests some comparison of these loads with those imposed by the engine drivers. The proposed 80-ton car will weigh about 50,000 pounds and the total weight of the loaded car will be 210,000 pounds, which, when carried by eight wheels, produces a static load on the rail of 26,250 pounds.

Weights on drivers have always greatly exceeded the load on smaller car wheels, and the reason for this seems to have been the greater strength of the larger wheels. Owing to the work locomotive tires receive in rolling they

* Railway Age Gazette, January 28, 1910. † Ibid., December 22, 1911.

FIG. 40. — Coke Car, All Steel. Capacity 100,000 lbs. Weight 47,600 lbs.

FIG. 41. — Stock Car, Steel Underframe. Capacity 100,000 lbs. Weight 47,400 lbs.

FIG. 42. — Vestibuled Coach, All Steel.

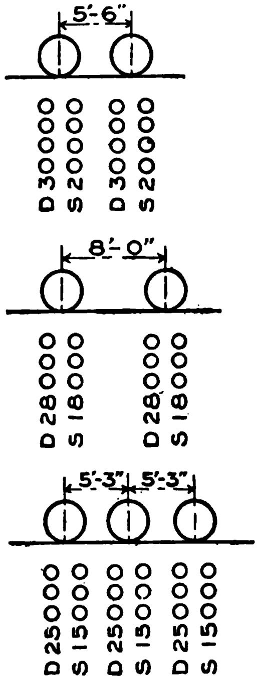
Fig. 43. — Twelve-section Sleeping Car.

Fig. 44. — Steel Combination Passenger and Baggage Car.

Fig. 45. — Vestibuled Dining Car.

Fig. 46. — Baggage Car, All Steel.

would appear better able to carry heavy loads than the smaller car wheels. While the loads on car wheels in themselves are not necessarily detrimental to the rail, it has seemed desirable to provide for the possible affect of a defective wheel by taking a relatively high dynamic augment of the wheel load.



Freight Cars.

	Lbs.
Weight of Car Empty	50,000
Weight of Load	100,000
10% Overload	10,000
Total	160,000

Passenger Cars.
4-wheel trucks.

	Lbs.
Weight of Car Empty	120,000
Weight of Load	20,000
Total	140,000

Passenger Cars.
6-wheel trucks.

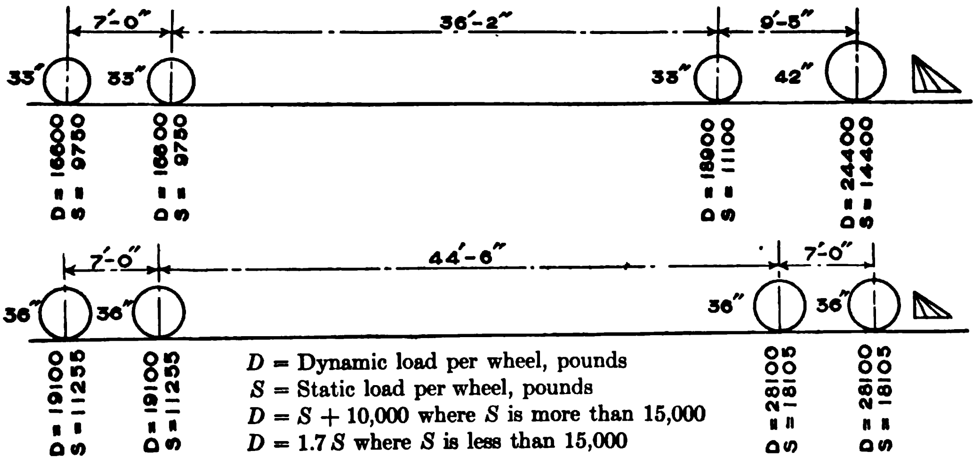
	Lbs.
Weight of Car Empty	160,000
Weight of Load	20,000
Total	180,000

D = Dynamic load per wheel, pounds
S = Static load per wheel, pounds
$D = S + 10,000$

Fig. 47. — Typical Load Diagrams for Cars.

Fig. 47 shows typical load diagrams for passenger equipment and freight cars.

Fig. 48 shows the dynamic wheel diagrams of motor cars used on steam roads, and Figs. 49 and 50 illustrate these cars.



D = Dynamic load per wheel, pounds
S = Static load per wheel, pounds
$D = S + 10,000$ where S is more than 15,000
$D = 1.7\,S$ where S is less than 15,000

Fig. 48. — Typical Dynamic Load Diagrams for Motor Cars.

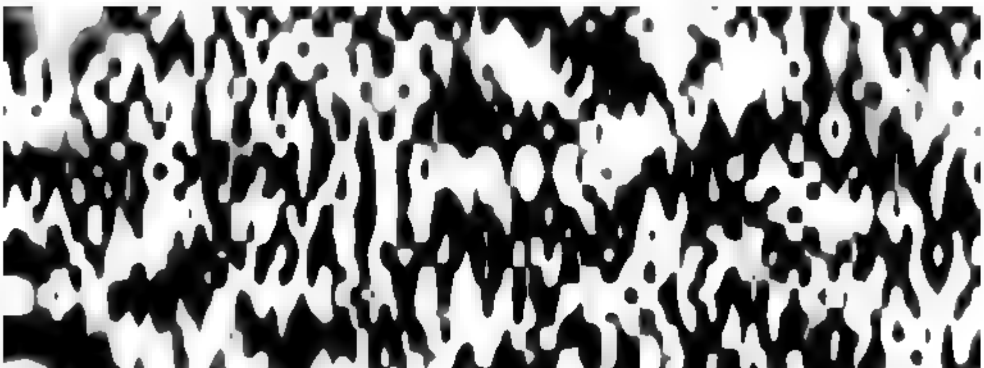
Fig. 49. — 70-foot McKeen Motor Car. Weight fully loaded, 90,000 pounds.

Fig. 50. — 70-foot General Electric Gas Electric Motor Car. Weight fully loaded, 117,440 pounds.

In Figs. 51 and 52 are given examples of the cars in use on electric railways, both for city service and on the longer runs of the interurban lines.

58-ft. "Single-end" Smoking and Express, Mail and Baggage Car.
Seating capacity, 38. Weight of car body, about 34,000 lbs.
Wheel base of trucks, 6′6″. Weight of trucks, 21,460 lbs.
Weight complete, about $38\frac{1}{2}$ tons.

62-ft. Buffet Observation Parlor Car.
Seating capacity, 35. Weight of car body, about 44,000 lbs.
Wheel base of trucks, 6′6″. Weight of trucks, 21,460 lbs.
Weight complete, about 44 tons.



51-ft. "Double-end" Special Parlor Car with Smoking Room.
Seating capacity, chairs 26. Weight of car body, about 29,000 lbs.
Seating capacity, seats 52. Weight of trucks, 20,322 lbs.
Wheel base of trucks, 6′6″. Weight complete, about 39 tons.

FIG. 51. — Electric Railway Cars (Niles Car and Mfg. Co.).

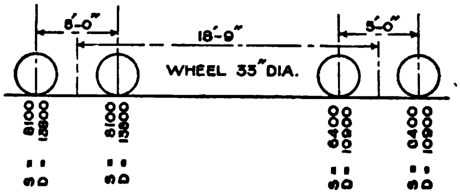
51-ft. "Single-end," Two-compartment, Fast Interurban Car.
Seating capacity, 52. Weight of car body, about 26,500 lbs.
Wheel base of trucks, 6'6". Weight of trucks, 18,600 lbs.
Weight complete, about 32 tons.

48-ft. Center-vestibule, Arch-roof, Steel Prepayment Car.
Seating capacity, 54. Weight of car body, 22,000 lbs.
Wheel base of trucks, 6'4". Weight of trucks, 16,132 lbs.
Weight complete, about 26 tons.

42-ft. Double-truck, "Single-end," Pay-As-You-Enter Car.
Seating capacity, about 45. Weight of car body, about 16,000 lbs.
Wheel base of trucks, 5'0". Weight of trucks, about 12,000 lbs.

FIG. 52. — Electric Railway Cars (Niles Car and Mfg. Co.).

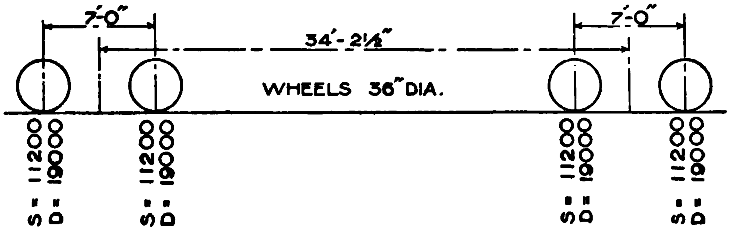
Fig. 53 presents the typical dynamic load diagrams of this class of equipment. The dynamic augment has been taken the same for these cars and the motor cars as was used for the freight and passenger cars on steam roads.



City Cars.

Weight of car and equipment	43,000 lbs.
Weight of passenger load (100 @ 150 lbs.)	15,000 lbs.
Total	58,000 lbs.

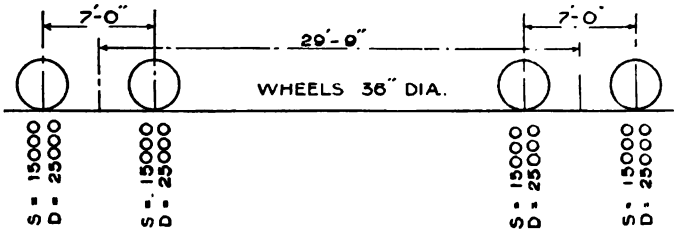
Equipped with two motors weighing 34,000 lbs. each, both motors on axle of the rear truck.



Interurban Passenger Cars.

Weight of car body	35,000 lbs.
Weight of trucks	24,000 lbs.
Weight of motor equipment	19,000 lbs.
Weight of passenger load (75 @ 150 lbs.)	11,250 lbs.
Total	89,250 lbs.

Equipped with four motors hung on four axles, so that the load is evenly distributed.



Interurban Freight Cars.

Weight of car and equipment	62,320 lbs.
Weight of load (rated capacity)	50,000 lbs.
plus 10 per cent overload	5,000 lbs.
Total	117,320 lbs.

Equipped with four motors, one motor to each axle.

FIG. 53. — Typical Dynamic Load Diagrams for Electric Railway Cars.

D = Dynamic load per wheel, pounds
S = Static load per wheel, pounds
$D = S + 10{,}000$ where S is more than 15,000
$D = 1.7\,S$ where S is less than 15,000

CHAPTER III

SUPPORTS OF THE RAIL

13. The Tie

The most common material used for the tie is wood. Some have suggested (and this suggestion is made with increasing frequency) that ties should be made out of materials other than wood. Granite ties were among the earliest substitutes offered; they were used for some time in Dublin, Ireland, and on the old Boston and Lowell Railroad in Massachusetts. For some fifty years various forms of metal ties have been suggested, and a large number of steel ties have been tried in various countries. In recent years concrete ties have been made.

Fig. 54. — Carnegie Steel Tie.

The following examples present in a general way what has been attempted as a substitute for the wooden tie. The list is far from complete, and must necessarily remain so, as new forms of metal and concrete ties are constantly being developed. The subject has been very fully reported upon by the committee on ties of the American Railway Engineering Association.*

Steel ties have been used quite extensively on the Union Railroad and on the Bessemer and Lake Erie Railroad. The total number of steel ties on these two roads is over one million or enough to lay 300 miles of track. There are a large number of steel ties of the Carnegie type (Fig. 54) in use throughout the country.

* See Report of Committee on Ties, Proceedings Am. Ry. Eng. Assn., 1909, 1910, 1911, and 1912, pp. 343–370.

Fig. 55 shows the insulated tie in use on the Bessemer and Lake Erie Railroad. The insulated tie is made by placing a piece of fiber on the steel tie and

Fig. 55. — Carnegie Steel Ties on the Bessemer and Lake Erie Railroad. (Am. Ry. Eng. Assn.)

Fig. 56. — Effect of Three Derailments on Steel Ties. (Am. Ry. Eng. Assn.)

then firmly riveting a steel plate over the top of the fiber for the rail to rest on. This is intended to stop all wear on the fiber.

Fig. 56 shows the effect of three derailments on the steel ties, which, in this case, merely bent down the upper flange of the ties, and in no way injured their usefulness as a tie.

FIG. 57.—Steel Tie after Four Years Service. (Am. Ry. Eng. Assn.)

Fig. 57 shows a steel tie taken from the track that had been in service four years. Very little rust was found on the web of the tie and the bottom flange of this tie showed very little corrosion. There were no signs whatever of the tie failing in any respect. The cutting of the slots or holes in the web of the tie, as shown in the figure, has been abandoned, as it was found that with slag or stone ballast the holes with the web turned out were not necessary in order to keep the track from sliding sideways.

The tie was smooth on the upper face where the base of the rail rests and showed very little, if any, wear. Providing the wear in years to come is no greater in proportion than it has been during the past four years, the tie would be good for 25 or 30 years.

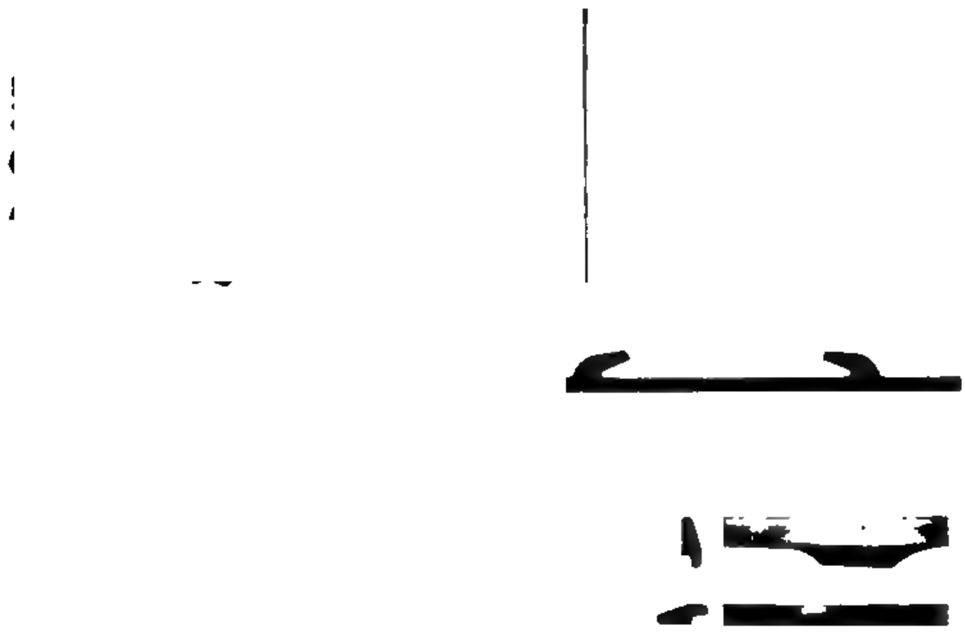


FIG. 58. — Carnegie Steel Tie with Wedge Fastener.

FIG. 59. — Hill Fastening on Carnegie Steel Tie. (Am. Ry. Eng. Assn.)

Fig. 58 shows the Carnegie steel tie with the wedge fastener.

Carnegie Steel Tie with Hill Fastening. — (Fig. 59.) Approximately 100,000 of these ties have been installed in yard tracks at the Duquesne Plant of the Carnegie Steel Company.

Fig. 60. — Hansen Steel Tie. (Am. Ry. Eng. Assn.)

Hansen Tie. — (Fig. 60.) Five hundred of these ties were placed in the track, July, 1905, near Emsworth, Pa., on the Pennsylvania Lines West of Pittsburg. A great deal of trouble was experienced with the insulation, also from the ties sliding transversely and longitudinally through the stone ballast, and the ties were in consequence removed from the main track in November, 1905, and placed in a passing siding.

Universal Metallic Tie. — (Fig. 61.) The figure shows these ties in the Pennsylvania Lines tracks near Emsworth, Pa. The design is the trough type, being a 6- by 8-inch by 8-foot steel channel. Holes are cut in the web of the channel on each side of the rail, and this metal is bent up vertically on each

side of a wooden block which fits in the channel under the rail. Clamps, fitting over the base of the rail and extending down vertically outside these bent-up portions of the channel, bind the block, rail and tie together. The clamp on the gauge side of the rail extends through the hole in the base of the channels about 4 inches into the ballast, giving an additional bond with the roadbed. A bolt, with a tapering head at one end and with a tapering washer at the other end, holds the connection tight. An insulating fiber is inserted between the rail and the clamp. The weight of this tie is 175 pounds.

Fig. 61. — Universal Metallic Tie on Pennsylvania Lines. (Railway Age Gazette.)

Fig. 62. — Snyder Steel Tie. (Am. Ry. Eng. Assn.)

Snyder Steel Tie. — (Fig. 62.) The illustration shows these ties in the Conemaugh yards of the Pennsylvania Railroad. There is also about one mile of these ties in use at Derry, Pa., on the same road, none of them being in the main tracks. The standard type of the Snyder tie consists of a steel shell $\frac{3}{16}$ inch thick, 8 feet long, 7 inches wide, 7 inches deep, and with the bottom open. The interior of the shell is filled with a mixture of asphalt and crushed stone. In 20 of the ties the mastic had disintegrated and fallen out of the ends of the ties after four years service. With this exception the Snyder tie has given very satisfactory service in the tracks of the Pennsylvania Railroad at Conemaugh and Derry.

FIG. 63. — Buhrer Combined Steel and Wood Tie on L. S. & M. S. Ry. (Am. Ry. Eng. Assn.)

Buhrer Steel and Wood Tie. — (Fig. 63.) The figure shows the fourth or freight track of the Lake Shore and Michigan Southern Railroad, east of Toledo, tied with the Buhrer combined steel and wood tie. Early in 1907 the Carnegie steel ties on the Lake Shore and Michigan Southern Railroad were removed from the high-speed track. To care for the insulation the top flange of the tie was cut off and two wooden blocks bolted to the web of the tie for spiking strips and for the rail to rest on. These strips also rest on the bottom flange of the steel tie.

Mexican Railway Tie. — (Fig. 64.) Practically the whole of the Mexican Railway system of 361 miles is laid with these ties. These ties weigh about 125

pounds, and cost $2.25. The ties are apparently giving excellent service. The axle load on this road, however, is not heavy on the light grades, and on the mountain grades, where axle loads as high as 50,000 pounds are employed, the speed is slow.

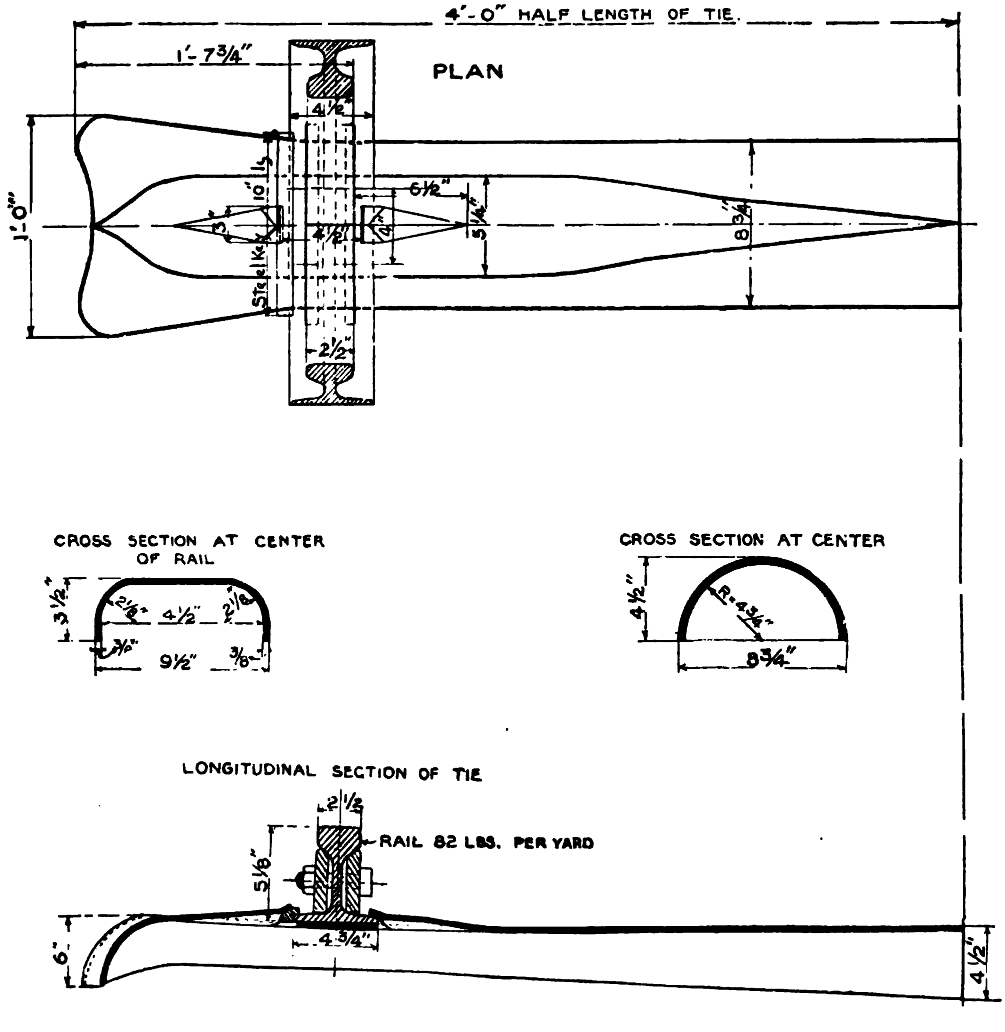


Fig. 64. — Mexican Railway Steel Tie. (Am. Ry. Eng. Assn.)

Buhrer Concrete Tie. — (Fig. 65.) About 600 of these ties were used on the Pennsylvania Lines west of Pittsburg during 1903 and 1904 in stone ballast. Nearly 500 were subjected to heavy and high-speed traffic and the balance to medium traffic. The ties failed under traffic, the concrete breaking and crumbling off from the reënforcement. The ties were removed from time to time and by December, 1906, all had been removed on account of breaking.

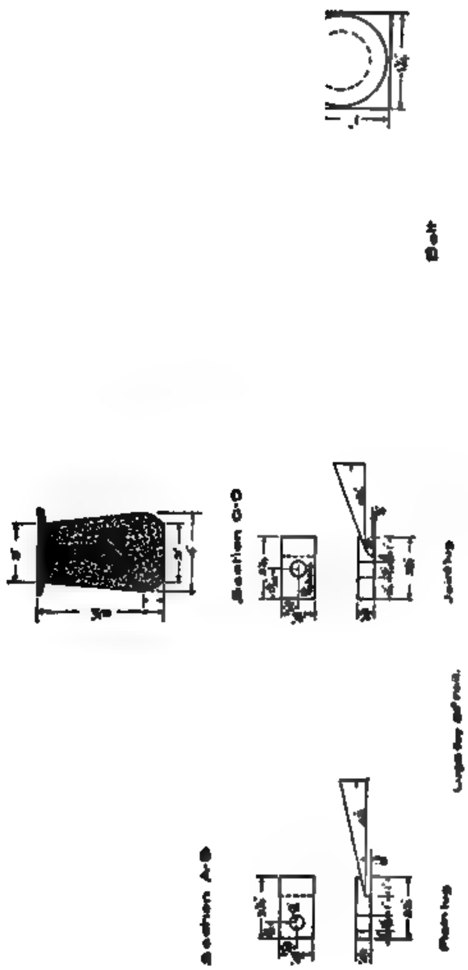


Fig. 65. — Buhrer Concrete Tie. (Am. Ry. Eng. Assn.)

Fig. 66 shows the bottom or bearing surface of this tie, which illustrates how the concrete is left out at the center to provide against side motion.

FIG. 66. — Bottom Surface of Buhrer Concrete Tie. (Am. Ry. Eng. Assn.)

FIG. 67. — Section of Track on Chicago and Alton R. R. showing Kimball Tie.

Kimball Concrete Tie. — (Fig. 67.) This figure shows the Kimball tie in the track of the Chicago and Alton Railroad, near Lockport, Ill., during October,

FIG. 68. — Kimball Tie put in Track on N. Y. C. & St. L. R. R., July, 1904.
Photograph taken January, 1909.

FIG. 69. — Kimball Tie Showing Spiking Plugs. (Am. Ry. Eng. Assn.)

1905. The track is kept in good condition, but several of the ties have developed cracks which may be due to improper application. Fig. 68 presents further examples of the Kimball tie, and Fig. 69 shows a tie in good condition, taken from the track. In this tie the spikes entered the spiking plug and the concrete was not damaged, as was found to be the case in most of the ties which

FIG. 70. — Percival Concrete Tie. (Am. Ry. Eng. Assn.)

developed cracks. Ties were not rusted to any extent in the center of the track between concrete ends. In 1912 there were about sixty Kimball ties in successful use in the track of the Chicago and Alton Railroad, the ties having been installed in 1905.

Percival Concrete Tie. — (Fig. 70.) The figure shows ties which were used on the Pittsburg and Lake Erie Railroad for about two years. They were

removed from the track in 1908 for the reason that the ties failed. The figure illustrates very plainly how and where these ties failed.

The Sarada and Adriatic Railway ties, given in Figs. 71 and 72, illustrate concrete ties used on the continent, and Fig. 127 shows the combined wood and metal ties used in France.

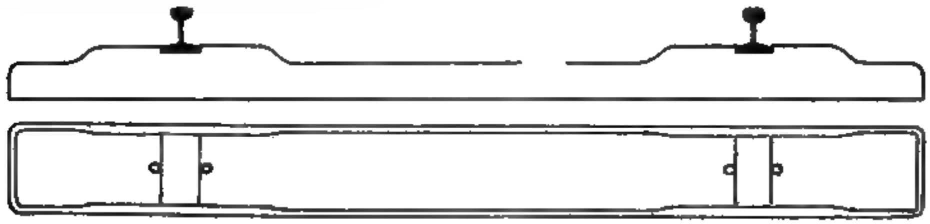


FIG. 71. — Sarada Tie. (Concrete Review.)

Sarada Tie. — (Fig. 71.) 3.9 inches in center and 5.9 inches under rails by 9½ inches by 8 feet long. Reinforcement, 4 sheets of expanded metal, set vertically and connected transversely by iron wires. The rail fastening bolts enter from below and are held in tubular castings embedded in the ties. Weight about 310 pounds.

FIG. 72. — Adriatic Railway Tie. (Concrete Review.)

Adriatic Railway Tie. — (Fig. 72.) Reinforcement, 29 rods having a total area of 3 square inches. The rail is fastened by bolts passing through the tie and inserted from below. The beveled rail seat is in accordance with European practice. Weight about 286 pounds.

Riegler Concrete Tie. — (Fig. 73.) Some of these ties have been in service on the high-speed tracks of the Pennsylvania Lines for several years without showing signs of deterioration. The ties have a large bearing surface and fifteen are used for a 33-foot rail, instead of eighteen standard wooden ties.

The ties have rounded sides, which assist in distributing the downward thrust over a short distance on each side of the tie, and the reaction assists in holding the tie from slewing, all the ties remaining as first placed at right angles to

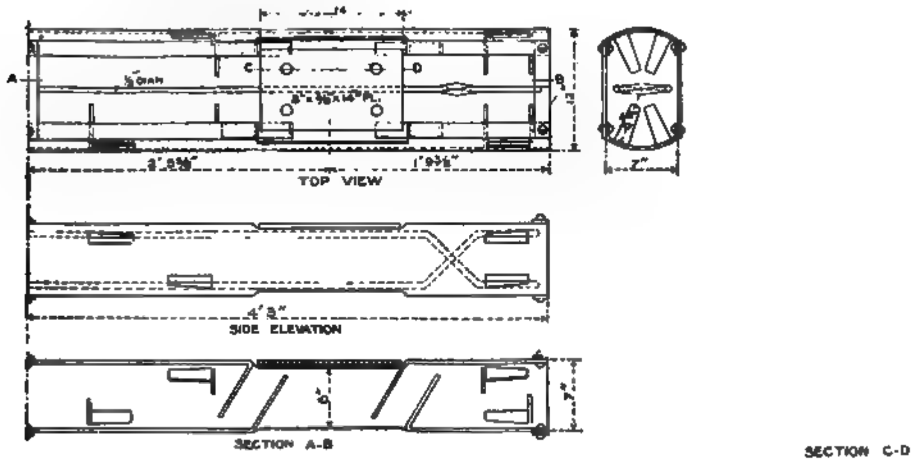


FIG. 73. — Riegler Concrete Tie.

FIG. 74. — Riegler Concrete Tie, Appearance in the Track. (Railroad Age Gazette.)

the track. The weight of the complete tie is about 850 pounds. It is proposed to cast a ring in the end to which a short rope can be attached for hauling into the track.

Table XVIII presents a summary of the service tests on concrete ties.

TABLE XVIII.—OUTLINE OF SERVICE TESTS OF CONCRETE TIES

(The Concrete Review, June, 1908, Coombs)

Name of Tie.	Railroad.	Location.	No. of Ties.	Date.	Track.	Alignment.	Remarks.
Harrell	P. F. W. & C. Ry.	Union Station, Chicago	30	1899	Main	Curve	2 cracked in 2 weeks but held together, 10 cracked in 6 months, all out in 1½ years, bolts loosened and disintegrated concrete (dry mixture).
	West. Fdy. & Steel Co.*	Hegewisch, Ill.	10	Aug. 1901	Siding	....	3 broken by a derailment, rest in good condition in 1904.
Affleck	L. S. & M. S. R.R.	Dune Park, Ind.	1	Sept. 1903	Siding	....	Some cracks within first year.
	L. S. & M. S. R.R.	Chestertown, Ind.	15	Jan. 1904	Siding	....	Some cracks within 6 months.
	Pennsylvania Lines	Emsworth, Pa.	87	Oct. 1904	Main	....	7 removed in 2 months.
Burbank	Hecla Belt Line	Bay City, Mich.	2	1904	Siding	....	Badly broken in 3 months.
Chenoweth	N. Y. C. & H. R. R.R.	72d Street, New York, N.Y.	18	July 1905	Yard	....	8 broken first day — all removed and not replaced.
		Scully	.....	1906	Yard	....	Heavy shifting.
	Inter. Rapid Transit	Dyckman St., N. Y.	.....	July 1905	....	....	
	Philadelphia Rapid Transit	Walnut St., Phila.	.....	....	....	....	Trolley line on paved street.
Brunson	Chicago Junction Ry.	Chicago, Ill.	19	1904	Yard	....	Cracked in 2 months — did not last through the winter.
Alfred	Pere Marquette R.R.	Saginaw, Mich.	14	Nov. 1902	....	....	All removed in 1904, account failure at center.
	Pere Marquette R.R.*	Saginaw, Mich.	9	1904	....	....	1 broken shortly afterward and others showed rail cutting in 3 months.
	....	Wixom	10	Sept. 1904			
	....	Saginaw, Mich.	214	Oct. 1904	Siding	....	56 immediately cracked or broken (ditch dug along side).
Seeley	Toledo Terminal Ry.	Toledo, Ohio	10	Aug. 1903	....	....	Failed in 2 weeks.
	L. S. & M. S. R.R.	Toledo, Ohio	6	....	Siding	....	Failed.
Ulster & Delaware R.R.	Ulster & Delaware R.R.	Rondout, N. Y.	1	May 1903			
	Ulster & Delaware R.R.	Rondout, N. Y.	.....	1904			
Blessing	C. B. & Q. R.R.	Hawthorne	.....	1904	Siding	....	No service tests to date.
Kneedler	Stockyard	Sioux City	.....	1906	Main	Curve	
Sarada	State Ry., France	Bordeaux	4	1900			
	State Ry., France	Bordeaux	100	1902			
	Northern Ry., Spain						
Adriatic	Adriatic Ry.	Ancona, Italy	.....	1900			

* Revised design. See report by E. O. Faulkner, A. T. & S. F. Ry., 1904.

TABLE XVIII.—OUTLINE OF SERVICE TESTS OF CONCRETE TIES—*Continued*

Name of Tie.	Railroad.	Location.	No. of Ties.	Date.	Track.	Alignment.	Remarks.
Voiron St. Beron	Voiron St. Beron Ry.	Revol, France	60	Mar. 1903			
Unciti	Northern Ry., Spain						
	State Ry., Germany	Briesen, Germany	.....	1897			
Hennebique	State Ry., France						
Kimball	Pere Marquette R.R.	Saginaw, Mich.	1	1900	....	....	Good condition '04, except checked cushion block.
	Pere Marquette R.R.	Saginaw, Mich.	2	1901	Yard	....	Removed — cause unknown.
	Pere Marquette R.R.	Saginaw, Mich.	8	....	Main	....	Good condition '04, except checked cushion blocks.
	....	Walkerville	2	Sept. 1903	Yard	....	Derailed trucks said to have done no injury.
	....	Pelton, Ontario	2	Sept. 1903			
	Nickel Plate	Euclid Ave Sta., Cleveland	8	1903			
	Chicago & Alton R.R.	Lockport, Ill.	80	Oct. 1905	....	....	Ties developed cracks.
Campbell	E. J. & E. Ry.	South Chicago, Ill.	344	1904-1905	Yard		
	E. J. & E. Ry.	South Chicago, Ill.	264	Jan. 1906	Yard		
	E. J. & E. Ry.	South Chicago, Ill.	36	April 1906	Yard	....	Where engine fires are cleared.
	E. J. & E. Ry.	South Chicago, Ill.	251	June 1906	Yard		
	E. J. & E. Ry.	South Chicago, Ill.	52	July 1906	Yard		
	E. J. & E. Ry.	South Chicago, Ill.	17	Sept. 1906	Yard		
	E. J. & E. Ry.*	South Chicago, Ill.	14	Oct. 1906	Yard	20° Curve	Rails spread $\frac{3}{4}$ — U bolts weak.
Hickey	Michigan Central R.R.	Kingsmill, Ontario	10	1902	Main		
	Michigan Central R.R.	Taylor	6	1902			
	Michigan Central R.R.	St. Thomas Yard, Ontario	.....	1902			
Buhrer	Pennsylvania Lines	Emsworth, Pa.	248	Dec. 1903	Main	....	100 replaced within 6 months (said to have been frozen before setting), and all had been removed by December, 1906.
				Mar. 1904			
	Pennsylvania Lines	Emsworth, Pa.	100	June 1904	Main		
	L. S. & M. S. R.R.						
	C. & N. Ry.	Allis Station, Milwaukee	15				
	Lake Erie & Western R.R.	....	20				
	Lakeside & Marblehead R.R.	Danbury, Ohio	550	1903	Yard	12° curve	
	Ann Arbor, R.R.	....	77	....	Main	5° curve	
Percival	Gal. Houston & Henderson R.R.	43d St., Galveston, Texas	25	June 1905	Main	Tangent	Heavy but not high-speed traffic.
	Florida East Coast Ry.	St. Augustine, Florida	.....	May 1906	.....	Tangent	
	Pittsburgh & Lake Erie R.R.	....	.....	Oct. 1906	.....	Tangent	Removed, 1908, on account of failure.
	Gal. Hbg. & San Ant. Ry.	Edgewater, Texas	.....	Oct. 1906	Main	Tangent	

* New design having 1 inch wooden block, but without the tie plate.

Probably no form of reinforced concrete tie has been made which is suitable for heavy and high-speed traffic. The real field of usefulness for the concrete tie appears to lie in its application in places where speed is slow and where conditions are especially adverse to the life of wood or metal.

The steel tie seems much more promising, but the fact remains that most of the railroads in this country to-day are using wood, and, so far as the author is able to judge from present tendencies, are likely to continue to do so for some time.

The question of a future timber supply for wood ties is a very important one. The railroads are rapidly exhausting the available timber near their lines and not only is the tie becoming dearer, but in many instances it is found impossible to obtain a sufficient supply to meet the annual requirements of the road.

The experience as set forth in a paper read at the American Forest Congress by Mr. L. E. Johnson, President of the Norfolk and Western Railway, is typical of most roads.*

"Originally the country passed through by the railroad was well timbered. The first extensive depletion of timber land was on the first hundred miles adjacent to the seaboard, where the original timber was cypress and virginia or loblolly pine.

"Up to the year 1888 the road used a great many cypress ties, but such timber is no longer procurable. The second growth of virginia loblolly pine in this district is very knotty, and, further, it is not suitable for crossties until it is treated to improve its lasting qualities.

"All the balance of the road is in territory where both white oak and chestnut oak is indigenous, and up to quite recently all the crossties that have been needed have been obtained within moderate hauling distance from the railroad line.

"The average requirements in oak ties per year for renewals are 310 per mile, aggregating, in round numbers, 800,000 ties per year for the entire road. At prevailing prices 800,000 ties cost per annum about $315,000, which is shown to be about 15 per cent over the cost of a like number ten years ago. This total is far below what some railroads less fortunately situated must pay for a like number."

The general distribution and character of the original forests † of the United States are shown by Fig. 75. A glance at this discloses that five groups

* Proceedings of The American Forest Congress, Washington, 1905, p. 265.

† The Timber Supply of the United States, Kellogg. Forest Service, Circular 97. Original Forests, R. S. Kellogg, Vol. 2, pp. 179, 180. Report of the National Conservation Commission, February, 1909.

FIG. 75. — Forest Regions of the United States. (Forest Service, Circular 97.)
The unshaded areas are treeless, except along the streams.

of states embrace the natural timbered areas of the country, — the Northeastern states, the Southern states, the Lake states, the Rocky Mountain states and the Pacific states. Of these, the two groups last mentioned are occupied by forests in which practically all the timber-producing trees are coniferous, the

first three of both conifers and hardwoods. The earliest attack was upon the white pine of the Northeast, the original stand of which is almost entirely cut out.

The Northeastern states reached their relative maximum in 1870 and the Lake states in 1890. The Southern states are undoubtedly near their maximum to-day, and the time of ascendency of the Pacific states is rapidly approaching. There will be no more shifting after the Pacific states take first place, since there is no new region of virgin timber to turn to.

The percentage of the total lumber cut, furnished by the principal regions since 1850, according to census figures, is given in Table XIX.

TABLE XIX. — GEOGRAPHIC DISTRIBUTION OF TOTAL LUMBER PRODUCT

(Forest Service, Circular 97)

Year.	New England States.	Lake States.	Southern States.	Pacific States.
	Per cent.	Per cent.	Per cent.	Per cent.
1850	54.5	6.4	13.8	3.9
1860	36.2	13.6	16.5	6.2
1870	36.8	24.4	9.4	3.8
1880	24.8	33.4	11.9	3.5
1890	18.4	36.3	15.9	7.3
1900	16.0	27.4	25.2	9.6

It is evident that at the present rate of consumption the available supply of the present timber used for ties, especially white oak and yellow pine, will be exhausted to a serious degree before many years, and that the railroads must consider the question of what course they are to pursue in the future.

Under these conditions there are obviously two courses: First, the reduction of the amount consumed, which can be done by the substitution of other materials for wood and by the use of preservative methods for prolonging the life of the tie, which, by increasing its durability, will diminish the annual requirements for renewals; second, by the adoption of forestry methods, having for their purpose the proper care and management of the forests still remaining and the cultivation of new tree plantations.

The question of forest preservation and perpetuation is beginning to receive attention in this country through the several State Bureaus of Forestry which have been established, and attention is given to forest preservation by these as well as by the National Government.

It has been found that the most important need for most of the railroads at this time is definite technical information. It is not sufficient to know that

timber supplies are being exhausted, but one should also know exactly what these supplies are, and what the rate of exhaustion is, and what the probable rate of regrowth is in any particular region upon which that particular road is depending.

The need of such investigation is being universally felt, and has manifested itself in very striking form, as shown by the two meetings of the governors of

FIG. 76. — Hunnewell Plantation (Catalpa). (Bureau of Forestry, Bulletin 37.)
Average diameter 3.85 ins., 21st year.

the various states, called by the President in May and December, 1908, in Washington, D. C.

Many tree species * in the United States are adapted to a certain degree at least for the production of crossties. Notwithstanding this, in making the majority of railroad plantations only two species have been used. These two species are catalpa and black locust.

Catalpa † has been planted for a great many years on a great variety of soils

* Proceedings Am. Ry. Eng. and M. of W. Assn., 1908, Vol. 9, p. 715.

† Practical Arboriculture, J. P. Brown.

and throughout a wide range of territory, and although many plantations have reached the age of twenty-five years or more,* so far as known, the trees in none of the plantations have reached a size suitable for crossties (Figs. 76 and 77). The black locust, although it is a rapid grower and thrives on a variety of soils, is so subject to the attacks of insects that trees seldom reach a sufficient size

FIG. 77. — Farlington Forest (Catalpa). (Bureau of Forestry, Bulletin 37.)
Average diameter 4.39 ins., 21st year.

to make a crosstie. Trees which do reach this size are usually so weakened by numerous cavities made by the boring of the insects that the wood cannot be used with safety.

Table XX shows that of the total number of trees planted, the locusts predominate, with the catalpa second; the results to date favor the former, although it is perhaps too early fairly to estimate the ultimate value of any of the plantations now under cultivation.

* The Hardy Catalpa, Bureau of Forestry, Bulletin No. 37. The Farlington Forest, p. 15. The Hunnewell Plantation, p. 26.

TABLE XX. — RAILROAD PLANTATIONS FOR TIE TIMBER

(Am. Ry. Eng. Assn.)

Railroad.	Locations.	Date.	Number.	Kind.	First Cost per M.	Cost Planting per M.	Per M. Annual Maintenance.	Synopsis of Replies from Railroads.
Chicago, Burlington & Quincy	Ottumwa, Iowa	1906	100,000	Catalpa	$10.00	$20.00	No figures available	N[illegible]
Pennsylvania.......	40 plantations between New Brunswick, N. J., and Altoona	Some each year, 1902 to 1909.	2,200,000 1,000,000 230,000	Black Locust Red Oak Mixed Species	$6.00 to $10.00 from Commercial Nursery. $3.00 to $5.00 now from Company Nursery	About $5.00 at present	Practically no charges for maintenance	Too early to now estimate returns, but are certain forest planting is best way to utilize outlying idle lands belonging to the company.
		Total ..	3,430,000					
L. & N. R.R.......	Eleven locations	....	868,930 570,000 630,800 14,650	Catalpa Walnuts Locust Poplar	.... $6 64	$23.44, includes maintenance charges to date	....	Unable to estimate ultimate value of the plantations for future cross-tie supply.
		Total...	2,084,380					
D. L. & W..........	Towaco, N. J., and Alden, N. Y.	1906 1907	44,000 50,000	Yellow Locust Yellow Locust	$23.03	$12.22	$1.20	Lost about 3,000 trees which were planted on low ground and did not stand the winter weather. Balance are thrifty and look well. Cannot now estimate ultimate value.
		Total...	94,000					
Galveston, Harrisburg & San Antonio R.R.	At section houses between New Orleans and El Paso, Texas	1908	15,000	Catalpa	$16.70	$12.00	$50.00	From results thus far obtained no reliable estimate of ultimate value can be made. Present re-[illegible]

TABLE XX. — RAILROAD PLANTATIONS FOR TIE TIMBER — *Continued*

Railroad.	Locations.	Date.	Number.	Kind.	First Cost per M.	Cost Planting per M.	Per M. Annual Maintenance.	Synopsis of Replies from Railroads.
Southern Railway.	Wolf Trap, Va.	1906	40,000	Catalpa	$19.40	$7 77	[illegible].64	Too early for any estimate as to ultimate value. Trees have secured [illegible] root growth and it is expected to cut all crooked and branched trees to ground line this winter About 5,000 seedlings failed to take root at time of planting.
Michigan Central..	Small plantations at section houses	1900 1903	80,000	Catalpa	....	....	....	Total of 123 acres planted. Latitude of extreme coldness was unsuitable for catalpa, and practically none of the trees grew.
Norfolk & Western.	Ivor, Va.	1906	2,000	Catalpa	....	....	....	S second growths, which are being held, only mature timbers being cut.
Pa. (N. W. Sys.)..	Kosciusko, Ind.	1906	35,000	Catalpa	$12 65	$10 46	$10.85	Can give no estimate of ultimate value.
S. A. & A. P. Ry...	Skidmore, Tex.	1909	22,000	Catalpa	$11.60	$27.10	$32 73	No remarks.
St. L. & S. F....	Farlington, Kas.	1880	.....	.....	....	....	....	640 acres planted, but only about 250 acres bore trees; balance were on poor, thin soil. Trees would never make ties because of poor soil, so were used for posts and poles.

Southern Pacific: Expect to soon start planting Sugar and Red Gum.
Union Pacific: Contemplate planting Catalpa on low lands owned by Company.
Delaware & Hudson Co.: Own large tracts in Adirondacks and are now making experiments to determine what trees are best suited to soils and climate.
Northern Pacific: Have reserved from sale several million acres of their timber lands; products from these tracts to be used for future tie supply.
C. C. C. & St. L.: Near Indianapolis; started small plantation some years ago; land used was not favorable and trees were not of proper species. Never obtained any results.

Tree planting as such by railway companies has not been a very successful matter, and it is generally felt that the planting should be regarded as supplementary to other methods for securing a tie supply, particularly to the management of forest lands.

There are, without question, large areas of timber in the South which can be obtained at a reasonable cost at the present time, and it seems to be very much more advisable to buy forest regions, or where cut-over lands are purchased, to encourage the growth of natural forest trees, rather than to go into extensive experiments for the planting of new trees.

Forest planting in some cases may be desirable when a railroad has waste land for which it has no particular use. It is a good object lesson to the farmers, and if the plantations are successful they will net a fair return on the investment and furnish a limited supply of tie and timber for the future.

It should be observed, however, that it would not be practicable for the individual roads to plant enough trees to supply their timber requirements, and further the critical period of scarcity and high prices would come before any of the trees so planted would reach maturity.

The information assembled by the Committee on Ties of the American Railway Engineering Association, in 1910 (Table XX), shows what has been done by the railroads in the way of tree planting; the situation is very little changed at the present time, and, in the opinion of those best able to judge, relief from this source is very uncertain.

If the railroads wish to provide against future scarcity and excessive prices with any degree of certainty it will be necessary for them to actively engage in forestry operations, having for their purpose the management of mature timberlands and the cultivation and reforestation of the cut-over lands within the forest area. This is an individual problem with every road, but, generally speaking, it is the only sound policy which will provide for the future requirements fifteen or twenty years hence.

Some of the railroads have now undertaken to preserve the timberlands which they acquired through land grants or otherwise. The Southern Pacific in northern California and southern Oregon still have quite large areas of good timber from which they can cut mature trees. The Northern Pacific has been coöperating with the government for some years with a view to finding how best to handle their western holdings, and provide a source of tie supply at the eastern end of their lines. In the East, the Delaware and Hudson have put about one hundred thousand acres in the Adirondacks under management.*

* Timber Supply in Relation to Wood Preservation, E. A. Sterling. Proceedings, American Wood Preserver's Association, 1911, pp. 140–144.

While the great desideratum is the obtaining of a permanent source of supply of tie timber, the economic side of the problem must as well be considered.

The application of actuarial methods to forestry is, despite the obvious difficulties about the assessments of the different factors used in making calculations, the only correct way of estimating the financial position of timber crops as a commercial investment.

The most profitable rotation is what should, both in theory and in practice, receive most consideration in the management of a forest. It is found by making various calculations, each as if for a single crop, in accordance with Faustmann's formula, and ascertaining that particular rotation which shows the greatest profit by indicating the maximum productivity or largest capital value of land and growing stock.

Faustmann's formula is as follows: *

$$A = \frac{F_n + (T_a \times 1.0\,p^{n-a}) + (T_b \times 1.0\,p^{n-b}) + \cdots (T_q \times 1.0\,p^{n-q}) - (C \times 1.0\,p^n)}{1.0\,p^n - 1} - \frac{g}{0.0\,p},$$

where A = The productivity of the woodlands (as estimated by the net value of the timber crop, etc.);

F_n = The net income, free from cost of harvesting, yielded by the mature fall at the year (n);

$T_a, T_b, \ldots T_q$ = The net income, free from cost of harvesting, yielded by the thinnings at the years $a, b, \ldots q$;

p = The percentage or rate of interest which the woodlands are supposed to yield annually on the investment represented by their capital value;

C = The cost of forming the crop originally, or of regenerating or replanting the area on the fall of the mature crop;

g = The annual outlay for general charges (supervision, protection, taxes, etc.).

After determining the most profitable period of rotation, the amount of land required to produce a given amount of ties annually can be found.

The cost per acre that can be paid for the land is determined as follows: The average annual charge, at present prices, for different kinds of ties may be taken as about 12.8 cents.

* The Forester, Nisbet, Vol. II, p. 239, London, MCMV; and Economics of Forestry, Fernow, New York, 1902.

This may be arrived at by the following relation. The discounted present value of an annual rental or return r obtainable for n years in all, the rate of interest being p, is expressed by the formula:

$$C = \frac{r\,(1.0\,p^n - 1)}{1.0\,p^n \times 0.0\,p} \quad \text{or} \quad r = \frac{C\,(1.0\,p^n \times 0.0\,p)}{1.0\,p^n - 1}.$$

In the case of a white oak tie,

C = \$ .90, cost of tie in the track, and r = \$ .14 annual charge.
n = 8 years, life of tie;
p = rate of interest, 5 per cent.

The table given below shows the annual charge for different kinds of wood.

White oak	14.0 cents annual charge
Heart pine	12.5 cents annual charge
Red oak, untreated	12.7 cents annual charge
Miscellaneous	12.0 cents annual charge

Assuming the life of a treated tie produced by the forest to be 12 years, the value of such a tie can then be expressed by the formula

$$C = \frac{r\,(1.0\,p^n - 1)}{1.0\,p^n \times 0.0\,p},$$

where C = value of the tie;
r = return or annual charge, 12.8 cents, obtainable 12 years in all;
p = rate of interest, 5 per cent.

Substituting these values in the formula, there results for the value of the tie \$1.13. From this there must be deducted:

Cutting	\$0.10
Handling	0.05
Treatment	0.30
Transportation	0.20
Putting in track	0.15
Total	\$0.80

which leaves for the stump value of the tie \$0.33.

The amount of ties produced by the forest will depend upon the kind of trees grown and the location of the tract. An annual yield of three ties per acre should be expected under careful management in most cases of moderately rapid growing trees. This will bring in a return per acre of:

R = 3 ties at \$0.33, less management and taxes \$0.30 = \$0.69, and the investment per acre which will give a five per cent return will be:

$$C_1 = \frac{R}{0.0\,p} = \$13.80.*$$

The wasteful methods employed in cutting ties in the past have called forth many protests and suggestions as to how this waste might be checked. The Forest Service states in this connection:

"The suggestions made for economy in the cutting of ties have been largely in the direction of preventing wasteful cutting. The manner in which they have been cut from trees has been largely determined by the ease and rapidity with which ties could be made, and by the knowledge that certain portions of a log were more serviceable for tie purposes than others.

"Ties were usually made out of heart wood, using the best and only the straight, live trees. No attention was paid to the waste incurred by cutting off all the sapwood top section, by leaving dead trees, etc. But with the introduction of treated ties certain new developments in tie making have taken place. Treated ties allow the use of sapwood, of sawed dead timber, and of sawed ties, consequently tie forms which were altogether impracticable under the old methods are now within the field of possibility, and must be considered on their merits."

In view of this Dr. von Schrenk has proposed a form of half-round tie which has been used extensively abroad (Figs. 78 and 79). The following description of the proposed form is taken from his excellent paper on Cross-Tie Forms and Rail Fastenings.†

This form of tie is probably a more economical tie than the present rectangular tie used in this country, and, on account of its proved merits, should properly be considered as a possible substitute for the present form.

If we consider the manner in which the load is distributed from the base of a rail resting on a 5-inch plate, which in turn rests on a tie 8 inches broad, we shall find that the lines of force acting from such a tie plate are distributed on the ballast as indicated in Fig. 80.

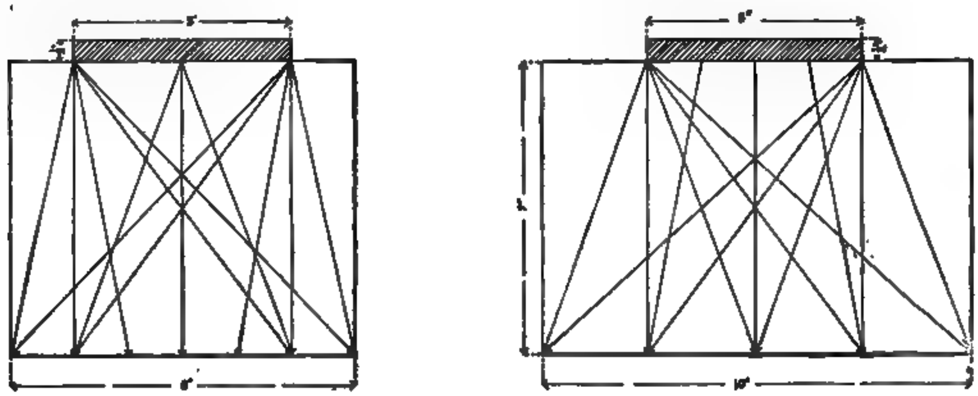
* The cost per acre that can be paid for the forest land is based upon the annual charge of untreated ties as representing the average outlay by the railroads for this material at the present time. The use of treated ties would probably reduce the annual charge per tie, but at the same time it must be borne in mind that owing to the rapidly increasing cost of the timber from which the tie is made, the annual charge for a treated tie will probably rise as high as the present figure for a natural tie, before sufficient time has elapsed for the treated ties to affect the general average.

† Cross-Tie Forms and Rail Fastenings, Von Schrenk; Bureau of Forestry, Bulletin No. 50.

FIG. 78. — Standard Prussian Ties of Baltic Pine. (Bureau of Forestry, Bulletin No. 50.)

FIG. 79. — Standard Oak and Beech Ties on the French Eastern Railway. (Bureau of Forestry, Bulletin No. 50.)

Keeping in mind the desirability of an increased bearing surface on the ballast, it is suggested that a type of tie with a top-bearing surface of about 6 inches and a base-bearing surface of anywhere from 8 to 12 inches will not only give a sufficient bearing surface for the rail, but will also give a much more stable track. Such a tie is shown in Fig. 81.



Distribution of Pressure from Tie Plate in Ordinary Tie.

Distribution of Pressure from Tie Plate in Half-round Tie.

FIG. 80. — Distribution of Pressure from Tie Plate.

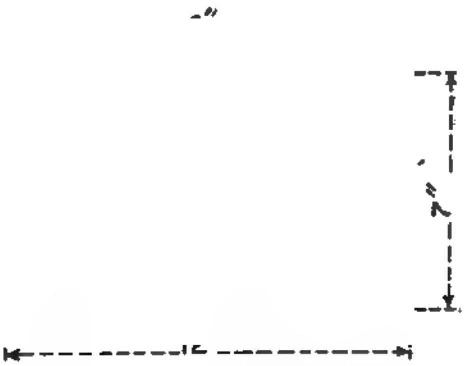


FIG. 81. — Half-round Tie Proposed by the Forest Service.

Fig. 82 shows the 7 by 8-inch tie and tie with 6-inch top and 12-inch base, spaced as closely as is consistent with the proper use of the shovel or other tool employed to tamp the tie.

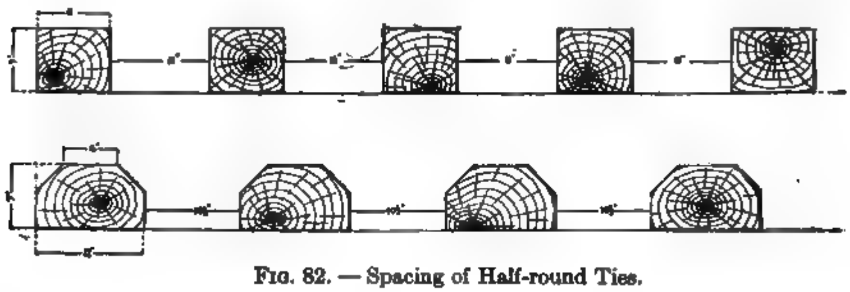


FIG. 82. — Spacing of Half-round Ties.

The comparative showing of rectangular 7 by 8-inch and 7 by 9-inch ties and of ties with 6-inch top and 12-inch base, spaced respectively at 11 and $10\frac{1}{2}$ inches, as shown in Fig. 82, is given in Table XXI.

TABLE XXI. — COMPARISON OF RECTANGULAR AND HALF-ROUND TIES

(Bureau of Forestry, Bulletin No. 50)

Items.	Rectangular Tie.		New Tie, 6-inch Top, 12-inch Base.
	7 × 8 inches.	7 × 9 inches.	
Distance between bearing centers, on both top and base of tie, inches	19	20	22.5
Increase in distance between bearing centers by use of ties of the new form, inches	3.5	2.5	....
Total number of ties per mile	3,242	3,168	2,816
Number of ties per mile saved by use of new form	426	352	....
Total linear bearing on ballast per mile, feet	2,161	2,376	2,816
Bearing surface on ballast per mile, with 8-feet length, square feet	17,290	19,008	22,528
Gain in bearing surface by use of tie of the new form, square feet	5,238	3,520	....

According to this table the number of ties of the new form required per mile is 352 less than with the 7 by 9-inch tie, and 426 less with the 7 by 8-inch tie, while the amount of bearing surface obtained is greater by 3,520 square feet than that obtained by the 7 by 9-inch tie, — an increase in bearing surface of over one-sixth. At the same time there would seem at first sight to be a considerable saving from the smaller number of ties, but in reality there is little difference in expense because of the larger number of feet, board measure, in the new tie.

It now becomes necessary to consider the changed tie form from a lumber standpoint. Ties are now being cut from trees of all diameters from 9 inches upward. If cut but one from a cross section, they are usually termed pole ties. Most of these are rounded at the edge and squared on two sides (Fig. 83), with a required bearing surface of 6 to 8 inches. Pole ties are now cut from trees as large as 17 inches in diameter. Most of them are hewn, and in the hewing much of the outer portion of the tree is wasted. In larger trees also a great deal of timber is wasted, even when ties are split in the most economical fashion. In the majority of instances no wane is admitted for a first-class tie, so that logs less than 10 inches in diameter will not make ties of this class. This means that a great many tops are now left in the woods because they are too small. By adopting the half-round tie suggested above (and here emphasis

FIG. 83. — Pole Tie.

ought to be laid upon the fact that ties cut according to this shape will all be treated) it will be possible to utilize a great many logs which now do not make ties, and also to cut a good many more ties out of the same amount of timber than under the present specifications.

The cutting of ties of this new form will be essentially a sawmill proposition. Where now there is a great deal of waste in hewing, if the log were sawed, it would mean the obtaining of several boards on the side. The number of boards to be sawed from a tree 16 inches in diameter, making two ties, will depend largely upon the value of the timber from which the ties are made. For instance, it will pay to make as many boards as possible out of a 16-inch, two-tie log of red oak or gum, while with timber like loblolly pine, the lumber of which has a low value, it will at present not pay to cut off many boards. In the case of such timber an extreme form of the half-round tie will be applicable (Fig. 84).

Fig. 84. — Extreme Form of Half-round Tie.

The influence which the new tie form will have upon the size of trees cut for tie purposes ought to be a marked one. It certainly would discourage the cutting of pole ties to a very considerable extent. It would not pay to make a tie out of a small tree when by leaving it for a few years two ties could be made from the same tree. In other words, the present policy of cutting trees 11 or 12 inches in diameter would be found less profitable than cutting trees 16 or 17 inches in diameter.

There is probably no other branch of the lumber industry in which so many small trees are annually destroyed and the possible regrowth of forests retarded to such an extent as in the manufacture of ties. The practice of sawing ties from logs is going to be more and more prevalent as the old feeling that a sawed tie is not worth having disappears. This feeling is already rapidly disappearing. It certainly will disappear entirely when railroad men realize that with a chemically treated tie it makes no difference whether it be sawed or hewn. With increasing permanency in the source of supply, it will pay more and more to put up small sawmills, which will saw ties and such lumber as may incidentally come to them. This will be particularly true in regions where there are rapidly growing tree species, such, for instance, as loblolly pine. The

cutting of these trees will, moreover, make possible the use of large quantities of timber which now is practically wasted and from which the lumberman has no return. This is particularly true of tops.

As the rail should be designed to have sufficient stiffness to enable it to distribute the load over a number of ties, allowing only such a proportion of the wheel load to come on each tie as can be safely carried, it will be necessary to determine the safe load that it will be proper to put on the tie. As a mean representing the average general practice, we may take in the following discussion a 7 by 8-inch by 8-foot 6-inch tie and a 7 by 9-inch by 8-foot 6-inch tie (see Table XXII). It would seem desirable also to consider the strength of the half-round tie.

TABLE XXII. — SIZE OF TIES AND SPACING

(Am. Ry. Eng. Assn.)

Railroad.	Size of Tie.	Number per Mile.	Railroad.	Size of Tie.	Number per Mile.
Southern	7×7 and 9×8½	2880	C., R. I. & P.	6×8×8	3200
Penn. R.R.	7×7 and 9×8½	2880	St. L. & S. F.	6×8×8	3200
L. & N.	7×7 and 9×8½	2880	Grand Trunk	6×8×8	3200
B. & O.	7×7 and 9×8½	2880	M., K. & T.	6×8×8	3200
N. & W.	7×7 and 9×8½	2880	Col. & Sou.	6×8×8	3200
P. & R.	7×7 and 9×8½	2880	Maine Central	6×8×8	3200
Penn. (S. W. Sys.)	7×7 and 9×8½	2880	C. & E. I.	6×8×8	3200
Lehigh Valley	7×7 and 9×8½	2880	C., I. & L.	6×8×8	3200
N., C. & St. L.	7×7 and 9×8½	2880	El. P. & S.-W.	6×8×8	3200
D. & H. Co.	7×7 and 9×8½	2880	St. L., B. & M.	6×8×8	3200
A., B. & A.	7×7 and 9×8½	2880	Ft. W. & D. C.	6×8×8	3080
Cent. of N. J.	7×7 and 9×8½	2880	C. & N.-W.	6×8×8	3000
B., R. & P.	7×7 and 9×8½	2880	C., M. & P. S.	6×8×8	3000
C., C. & O.	7×7 and 9×8½	2880	C., M. & St. P.	6×8×8	3000
A. C. L.	7×7 and 9×8½	2816	C. I. & S.	6×8×8	3000
Penn. (N. W. Sys.)	7×7 and 9×8½	2816	St. L. S. W.	6×8×8	2992
D., L. & W.	7×7 and 9×8½	2816	M. & St. L.	6×8×8	2992
Fla. East Coast	7×7 and 9×8½	2816	S. A. & A. P.	6×8×8	2992
C., C., C. & St. L.	7×7 and 9×8½	3300	Rutland	6×8×8	2992
Hocking Valley	7×7 and 9×8½	3050	Mo. & N. Ark.	6×8×8	2992
L. S. & M. S.	7×7 and 9×8½	3040	S. Fe, P. & P.	6×8×8	2900
Erie	7×7 and 9×8½	2720	L. E. & W.	6×8×8	2880
Long Island	7×7 and 9×8½	2720	G. R. & I.	6×8×8	2880
South. Pacific	7×9×8	2880	W. & L. E.	6×8×8	2880
Union Pacific	7×9×8	2880	N. W. Pac.	6×8×8	2880
S. A. L.	7×9×8	2880	Mo. Pac.	6×8×8	2816
N. Y., N. H. & H.	7×9×8	2880	B. & M.	6×8×8	2816
C. of Ga.	7×9×8	2880	K. C., M. & O.	6×8×8	2816
G., H. & S. A.	7×9×8	2880	Tenn. Cent.	6×8×8	2816
Georgia	7×9×8	2880	C. G. W.	6×8×8	2880
M. & O.	7×9×8	3164	C., H. & D.	6×8×8	3168
Norfolk Southern	7×9×8	2816	M. C.	6×8×8	3564
N. Y. C. & H. R.	7×9×8	3200	Bangor & Aroostook	6×6×8	2880
Great Northern	7×8×8	2880	N. Y., O. & W.	6×9×8	3120
S. P., L. A. & S. L.	7×8×8	2880	M., J. & K. C.	7×9×9	3168
Northern Pacific	7×8×8	2900	C., St. P., M. & O.	7×7×8	2816
D. & R. G.	7×8×8	3200	D., S. S. & A.	7×7×8	2730
C., B. & Q.	6×8×8	3200			

14. Bearing of the Rail on the Tie

The general tendency at the present time is more and more towards the use of tie plates. With the introduction of the treated tie it is necessary to adopt some means to protect the wood from wear at the rail bearing on account of the longer life of the tie.

The objections which have been made to tie plates were, first of all, that they buckled severely. This, however, has taken place only when the plates were too thin, and the following record of tests made of a prominent make of tie plate show that the present plates have ample strength to resist buckling (Table XXIII and Fig. 85).

Fig. 85. — Test on McKee Tie Plate.

Most plates have been made with the idea of being anchored to the tie so as to prevent the communication of the motion of the rail to the plate. As a result, we have a large number of different forms of plates, provided with prongs, spines, or flanges on the bottom, which are pressed into the tie either by the weight of the passing load or before the rail is laid (see Plate XXII).

TABLE XXIII.—TEST OF McKEE TIE PLATE

Loads as Applied, Pounds.	Test No. 1, Deflection Inches.	Test No. 2, Deflection Inches.
250	000	.000
4,000	022	[illegible]
8,000	029	.030
12,000	.035	038
16,000	042	.056
20,000	.054	.070
24,000	.066	.081
28,000	.[illegible]	.100
32,000	.101	129
36,000	.122	.165
40,000	.154	.210
44,000	.188	.248
48,000	.221	.285

The chief objection which is made to plates at this time, particularly in connection with the use of softer woods, is that not only do they not aid in preventing the wear of fibers, but they actually assist the rail to wear. This is well illustrated in Fig. 86, showing a tie plate which has been in position on a loblolly pine tie for about four years.

The constant rocking motion of the rail, which had become very marked as the spikes were pulled from the soft wood, had transmitted itself to the tie plate, and when a load passed over the rail the tie plate moved back and forth

in unison with the rail. It was not long before the soft fibers of the loblolly pine suffered under this treatment, and in the course of time so great did the abrasion and crushing of the fibers by the plate become that a considerable hole was made under the plate, in which water gathered. The plate gradually sank

FIG. 86. — Wear of Tie under Tie Plate.

The upper illustration shows a Loblolly Pine Tie treated with Zinc Chloride, after four years' service in Texas.

The lower illustration shows a longitudinal section through the spike hole of a Western Yellow Pine Tie after several years' service in Texas.

(Bureau of Forestry, Bulletin No. 50.)

down into this hole, as shown in the illustration. When the tie was removed it had disappeared in the wood, and the base of the rail was resting on the outer edges of the tie beyond the plate.

This tie had been treated with zinc chloride. The water which gathered under the tie plate leached out the salt, and as a result decay started on both sides of the plate, as the illustration shows. The tie had to be removed, although the rest of it was perfectly sound (Figs. 87 and 88).

FIG. 87. — Section of Tie under Rail Bearing showing Wear and Decay

FIG. 88. — Section from Middle of Same Tie showing Entire Soundness.

LOBLOLLY PINE TIE TREATED WITH ZINC CHLORIDE, AFTER FOUR YEARS' SERVICE IN TEXAS.

(Bureau of Forestry, Bulletin No. 50.)

The types of plates used in Europe are without exception flat plates.* Figs. 89 to 96 represent plates used by several European roads at the present time.

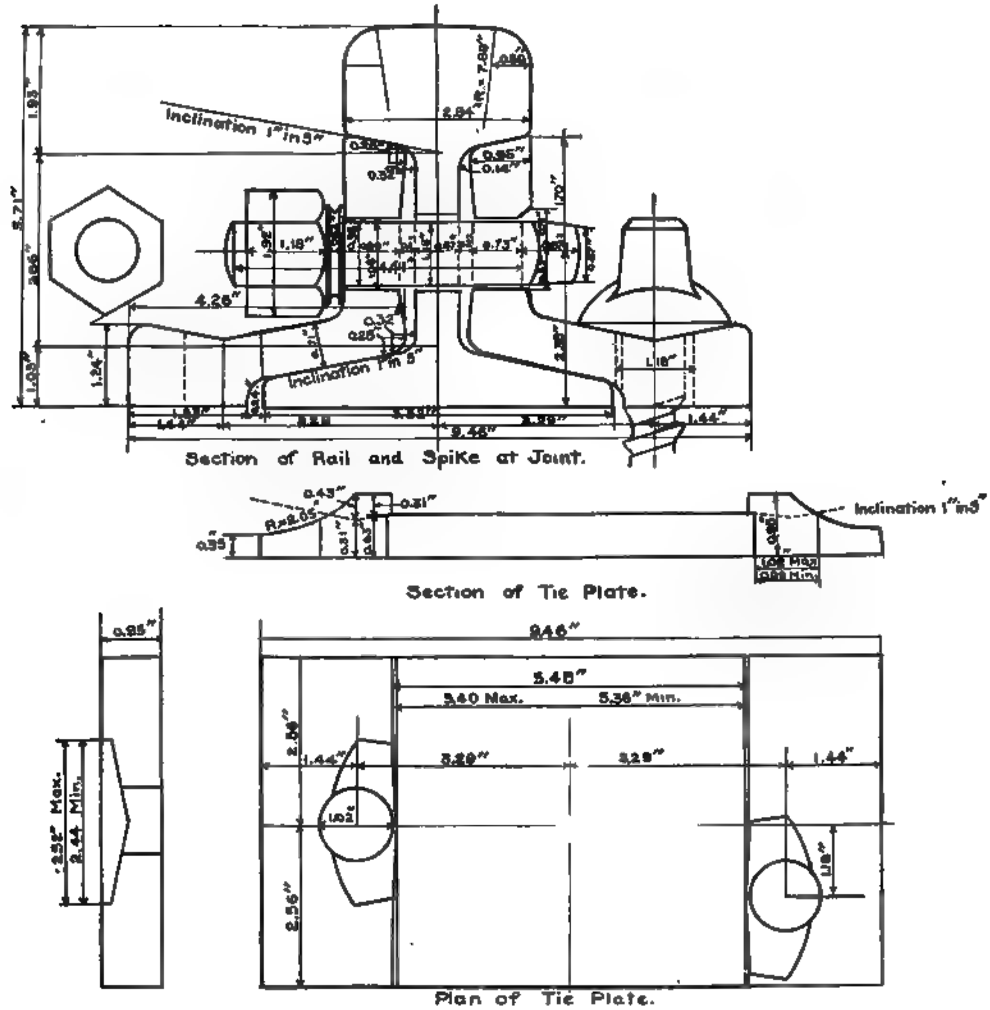


FIG. 89. — Belgian State Railways, 105-lb. Rail and Tie Plate. (Am. Ry. Eng. Assn.)

* See "The Question of Screw Fastenings to Secure Rails to Ties." W. C. Cushing, Proceedings Am. Ry. Eng. and M. of W. Assn., 1909, Vol. 10, Part 2.

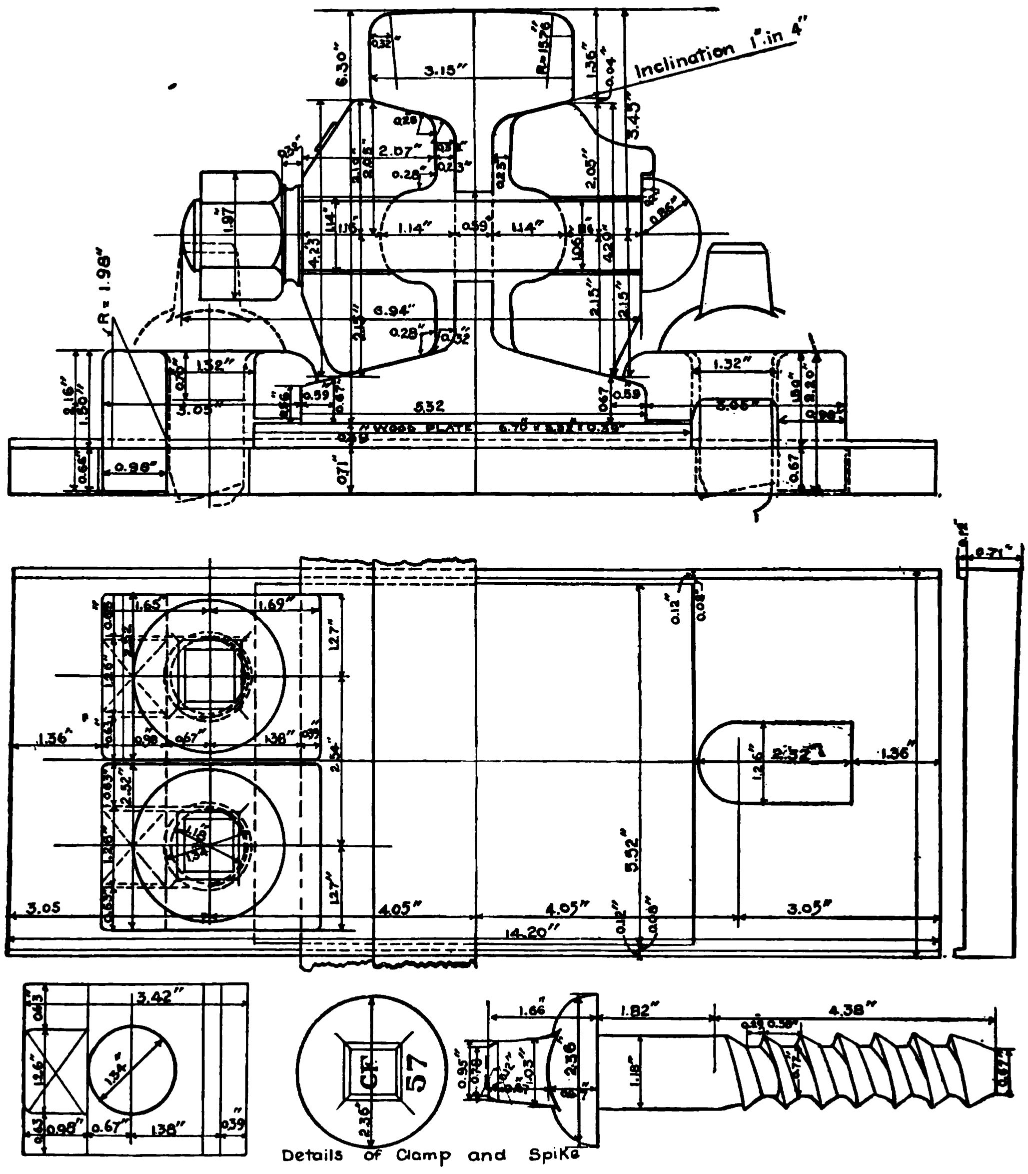


FIG. 90. — Belgian State Railways, 115-lb. Rail and Tie Plate. (Am. Ry. Eng. Assn.)

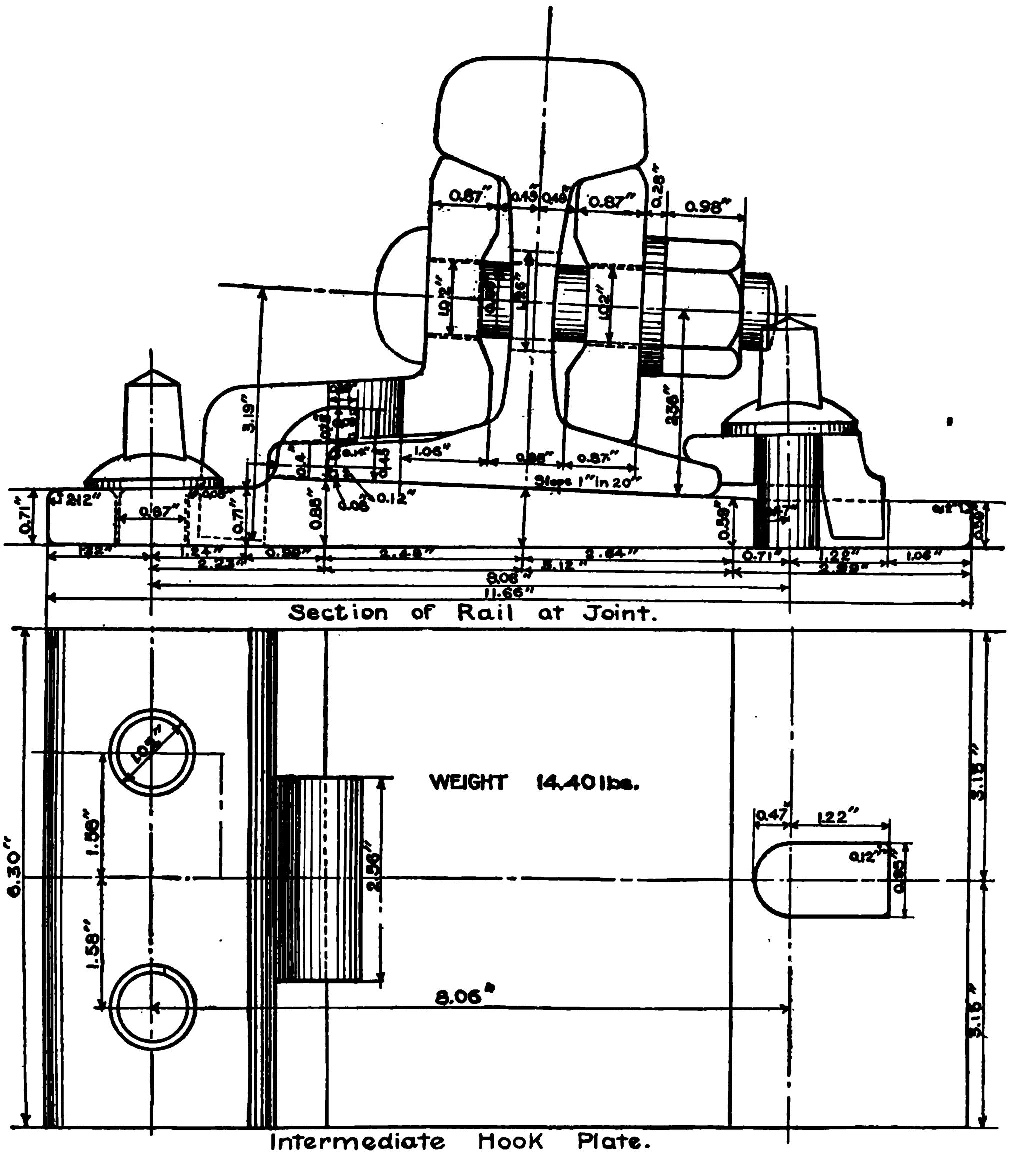


FIG. 91. — Kingdom of Württemberg State Railways, Tie Plate. (Am. Ry. Eng. Assn.)

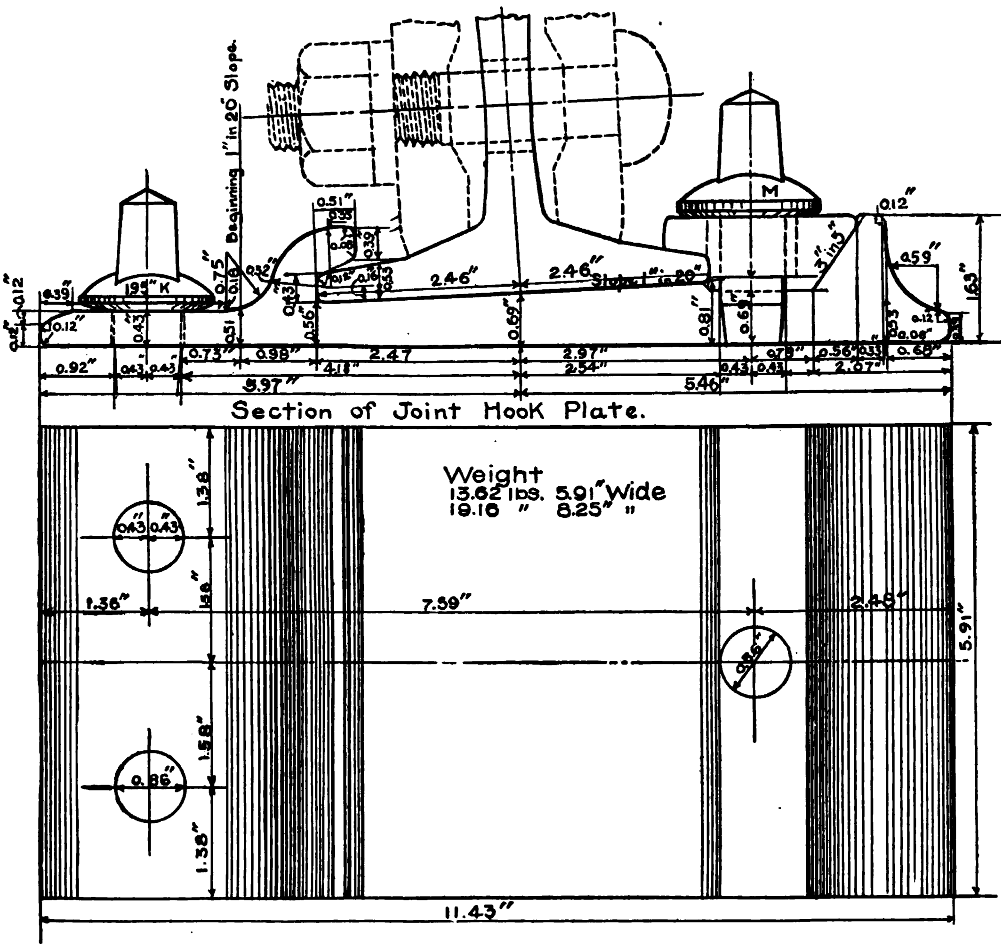


FIG. 92. — Bavarian State Railways, Joint Hook Plate. (Am. Ry. Eng. Assn.)

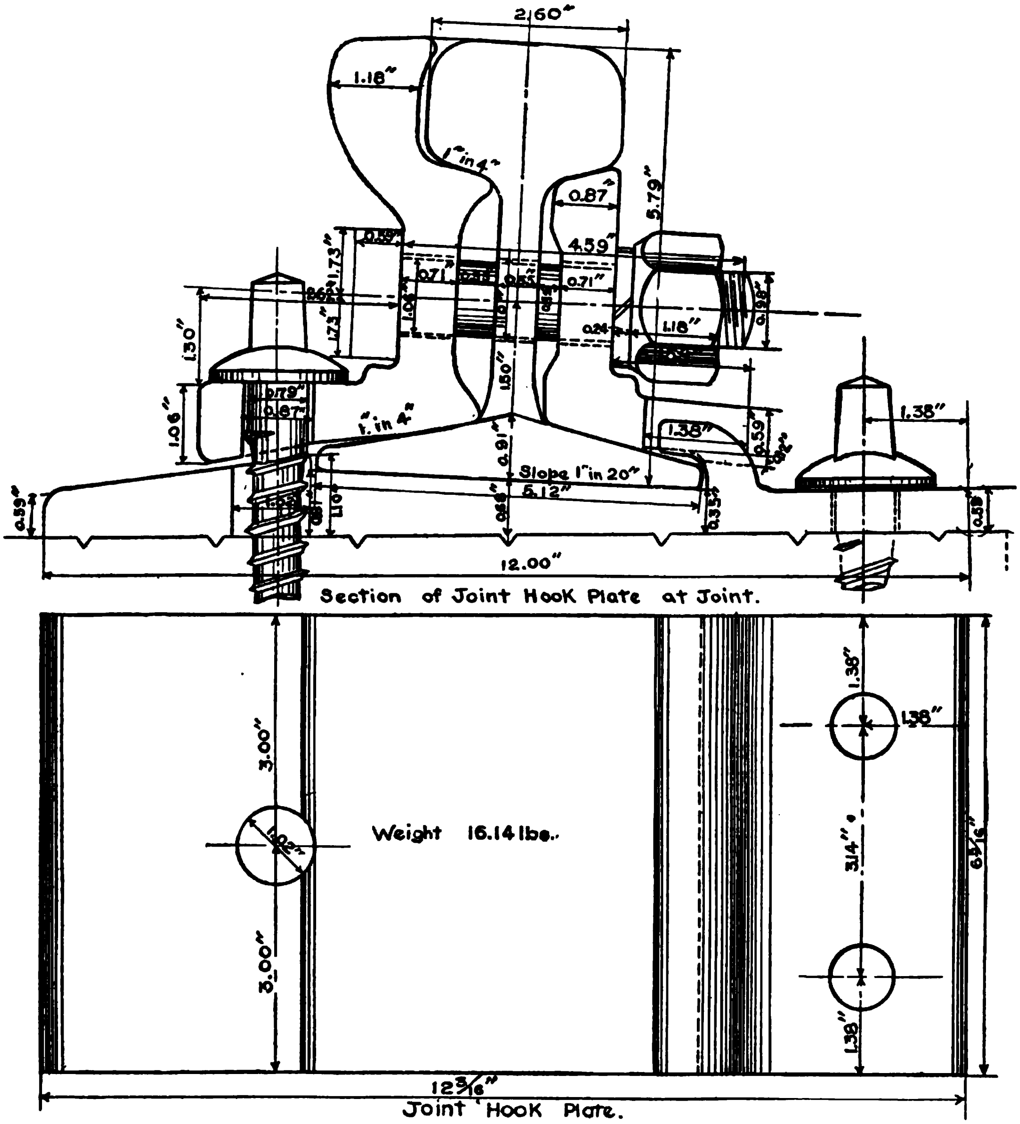


FIG. 93. — Kingdom of Saxony State Railroad, Joint Hook Plate. (Am. Ry. Eng. Assn.)

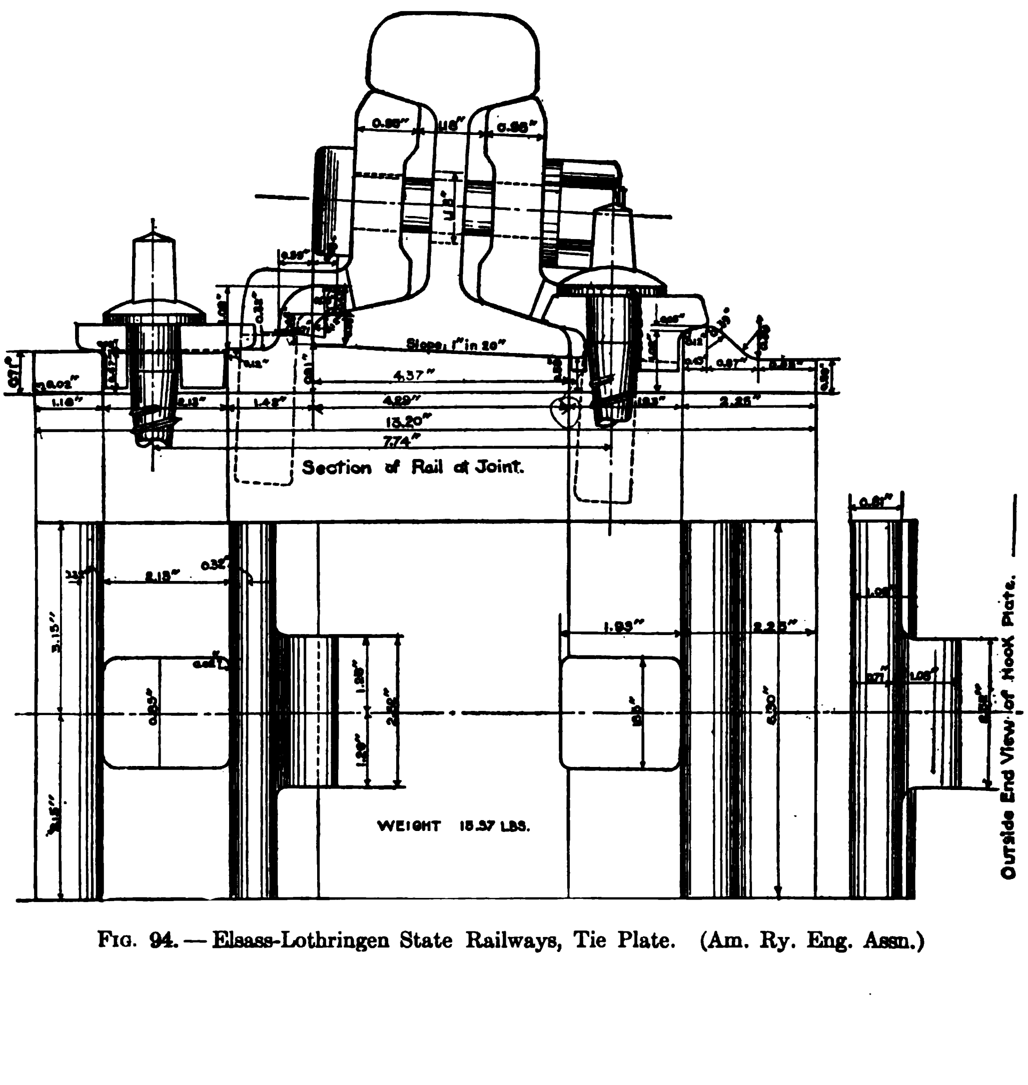


FIG. 94. — Elsass-Lothringen State Railways, Tie Plate. (Am. Ry. Eng. Assn.)

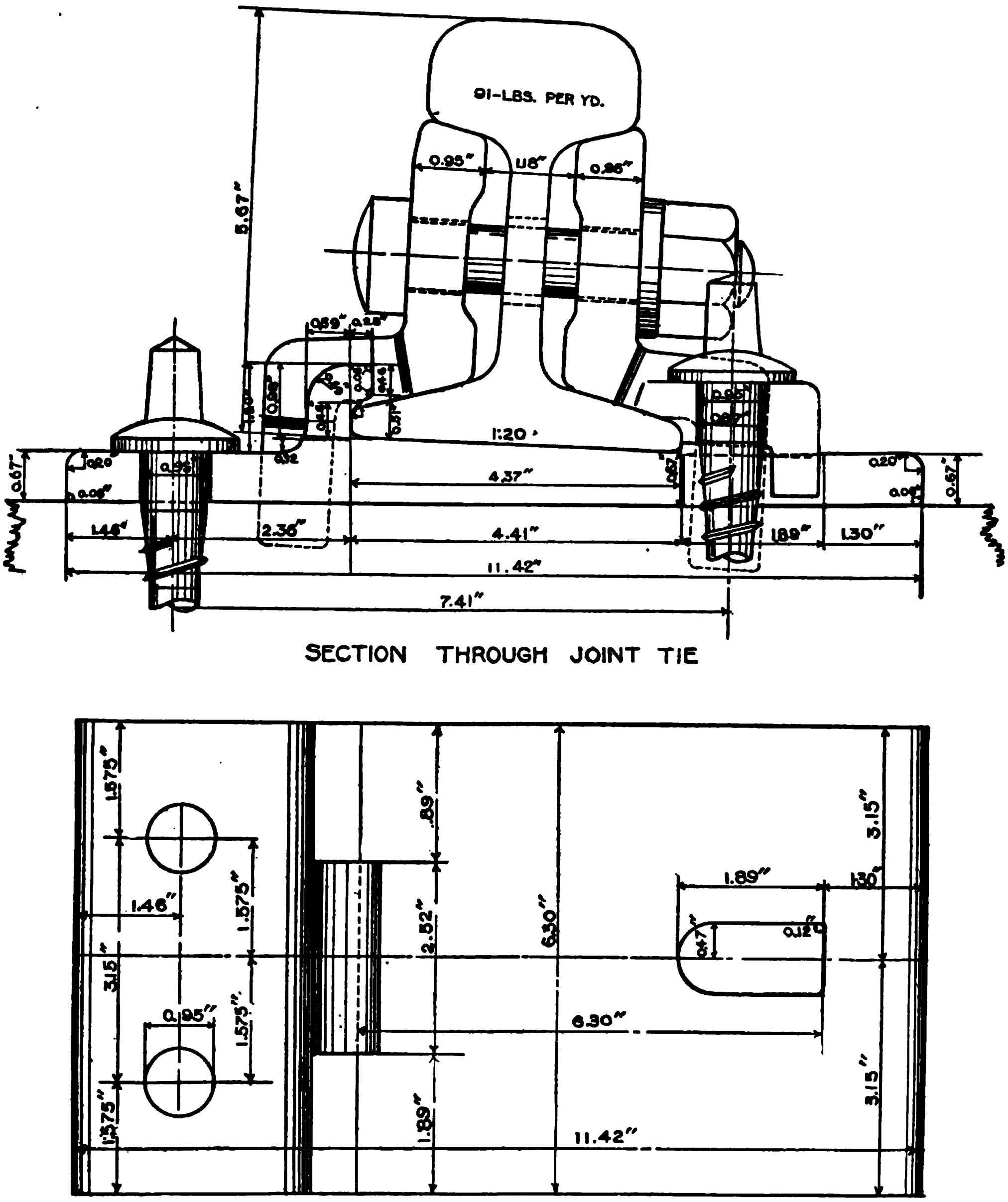


FIG. 95. — Prussian State Railways, Tie Plate. (Am. Ry. Eng. Assn.)

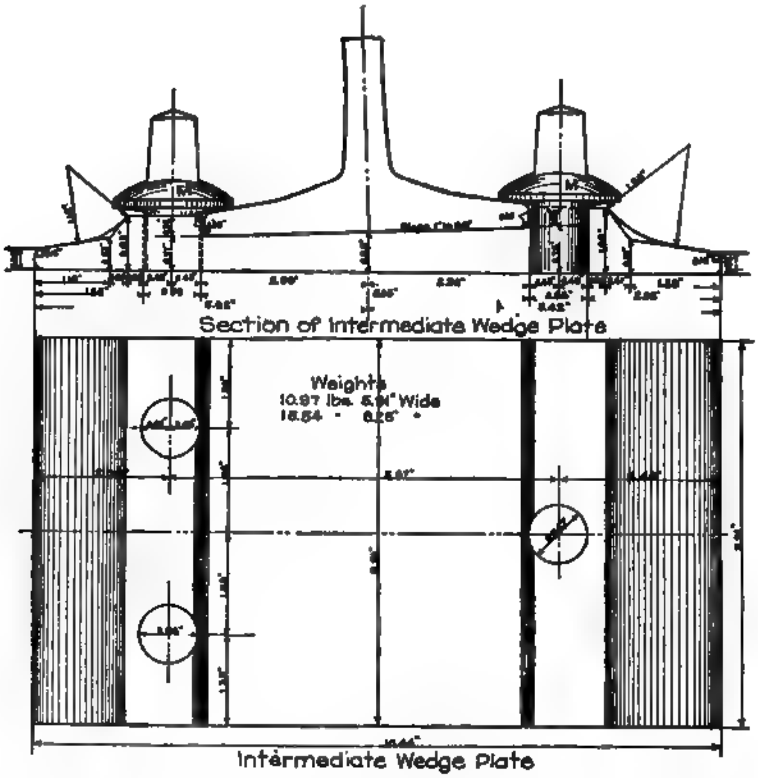


FIG. 96. — Bavarian State Railways, Intermediate Wedge Plate. (Am. Ry. Eng. Assn.)

The general tendency on the Continent has been toward adopting more and more rigidly flat plates, with firm fastenings. The almost universal adoption of this principle is very striking at the present day.

On the French Eastern* the rail rests on the tie without metallic plates, except on very sharp curves (of 984.25 feet radius and under). Plates of poplar or felt are placed under the rail, solely to protect the wood against the mechanical action of the base. These plates are compressed before being used, so that they will not be further compressed under the pressure of the rail. The plates are furnished 0.28 inch thick, and the compression brings them to 0.16 inch.

FIG. 97. — Wooden Tie Plate on French Eastern.

* Bureau of Forestry, Bulletin No. 50, von Schrenk.

The ties are adzed at the treating plant so that a place is left for this flat wooden shim. When the track is laid, the shim is placed in position (Fig. 97) and screw spikes are screwed into the tie. Their pressure holds the plate firmly between the base of the rail and the tie. In Fig. 97 the wooden tie plate is represented by the thin unshaded portion between the rail and the tie. It is exactly the width of the rail. In the course of time the motion of the rail wears out this shim, and a new one is substituted by giving the screw spike one or two upward turns. A new plate is then shoved in endwise and the screw is fastened. The length of life of one of the wooden shims on the main-line tracks, such as that of the French Eastern from Paris to Strassburg, is about one and one-half to two years.

Dr. von Schrenk gives the theory upon which this wooden plate is used as follows: The principal function of the plate has been said to consist of preventing the wear of the fibers of the tie immediately under the rail base. This wear consists in the actual breakage of the wood fibers under a grinding and tearing action rather than in crushing them.

In considering the function of the tie plate we have three bodies to deal with: the tie, the tie plate, and the rail. Motion might conceivably take place either between the rail and the tie plate or between the tie plate and the tie. When a metal tie plate is used on the hardwood tie, and is successfully anchored in it, the tie plate and the tie act as one body, over which the rail moves back and forth. As soon as the tie plate loses its holding power, however, the chances are that when the rail moves across the tie the tie plate will oscillate back and forth in unison with the rail. This results in breaking the wood fibers underneath the plate. Where a wooden plate is used, it adheres so closely to the wood that when the rail moves across the tie the wooden plate and the wooden tie are liable to act as one, even though the tie plate is not anchored to the tie.

The Forest Service tests have not shown results favorable to wooden tie plates. While the tests have not been very thorough, they have been thought to throw much doubt on the efficiency of this form of plate.

* For some years the question of a satisfactory fastening between rails and soft-wood ties has been a subject of continuous experiments on the Prussian Government railroads. The first investigations followed the general use of plain bearing plates, $7\frac{1}{8}$ by $6\frac{1}{4}$ inches (rolled steel) in size, shown in Fig. 98 *a*.

* Fastening of Rails to Soft Wood (Pine) Ties, Organ für die Fortschritte des Eisenbahnwesens, May 15, 1908, et seq. Translation appears in Vol. 10, Part 2, Proceedings Am. Ry. Eng. & M. of W. Assn., p. 1533.

It was soon discovered that on soft-wood ties, the small adhesion between the spike and the wood permitted the spikes to pull out to a more or less extent, and the loose rail, under the sudden applications of load, would quickly batter down the wood. Besides, the pressure on the tie not being uniform would produce a kind of convex wear in the wood, as illustrated in Fig. 98 *b*.

Some improvement was obtained by the use of screw spikes, without, however, entirely overcoming the abnormal wear and the consequent looseness

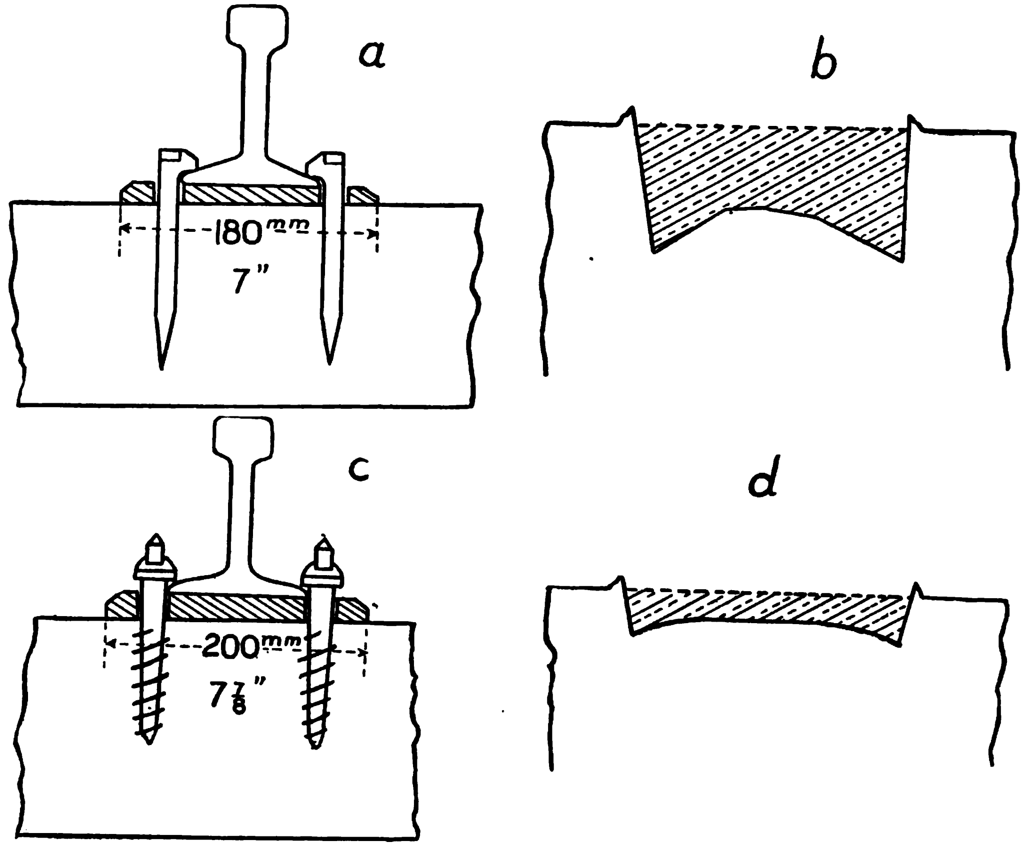


FIG. 98. — Plain Bearing Plates, German Experiments on Tie Plates.

and inefficiency of the structure (Figs. 98 *c* and *d*). The hook plate, shown in Fig. 99 *a*, was next tried. The hook, which was made to hold the outside flange of the rail, necessitated a plate somewhat longer on the outside than on the gage side, resulting in an uneven distribution of pressure on the wood and a condition as shown in Fig. 99 *b*. The bending of the screw spikes observed in this case was at first thought to be due to the lack of support of the head of the spikes on the far side from the rail flange, and, to remedy this supposed defect, rail clips were introduced, giving the head of spikes a full support all

around (Fig. 100 *a*). This arrangement proved to be much better than any previous one, but still did not produce a satisfactory fastening. Fig. 100 *b* indicates clearly the manner of failure of these plates.

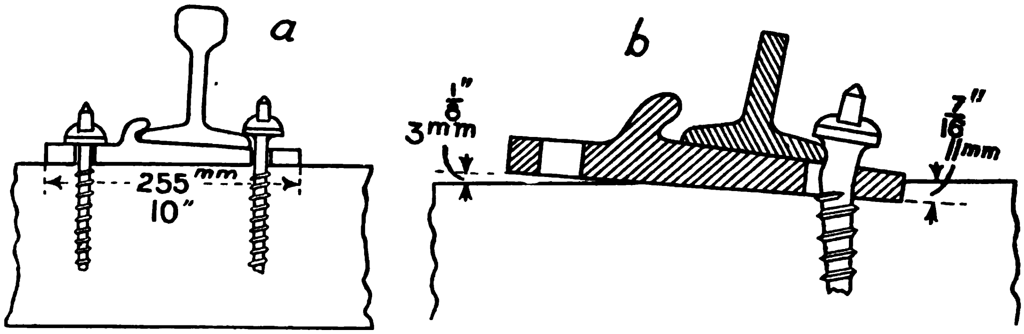


FIG. 99. — Hook Plates, German Experiments on Tie Plates.

It is evident that the plate hook, being rigid and incapable of producing any actual pressure against the rail flange, would cause all the stresses to be carried against the screw fastening, and as soon as this would wear in any of its parts the rail would become loose under the hook, and the shocks would

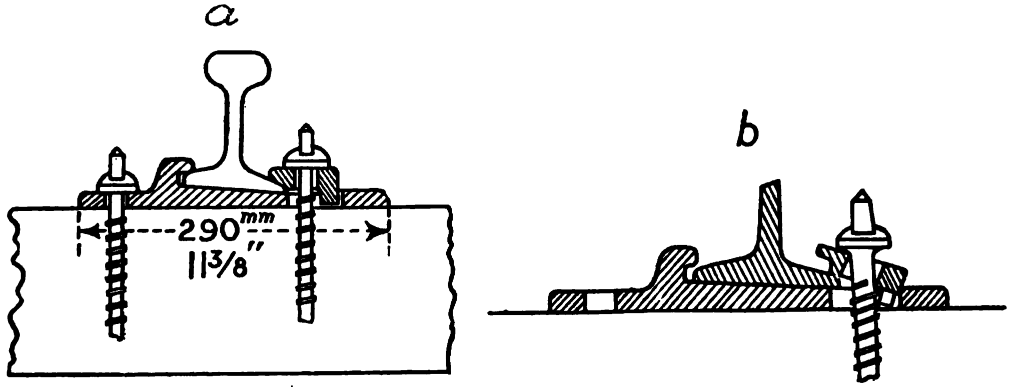


FIG. 100. — Hook Plates with Clips, German Experiments on Tie Plates.

begin their destructive work. Also, the direct pressure under the head of the spikes would tend to pull these out of the tie, and constitute another element of weakness to the general construction.

The impossibility of fastening the rail with the same amount of holding power on both sides, besides the drawbacks enumerated above, led to the introduction of an entirely different system of fastening.

The first set, or Group 1, of plates are shown in Fig. 101. These plates had a bearing on the ties of 90 square inches as against 80 square inches in the largest previous plate, and were fastened to the ties by means of four screw spikes absolutely independent of the rail fastening. The rail was in its turn

fastened to the plate by means of two bolts and clips, these being independent of the tie fastening.

The clips were made so as to be capable of adjusting the gage of the track by being reversible, and also of such a shape as to take up and transmit horizontal forces at the base of the rail to the shoulders provided for in the tie plates. In this manner the upward forces would be resisted by all the screw spikes, and similarly all the horizontal forces would be taken care of. Spring

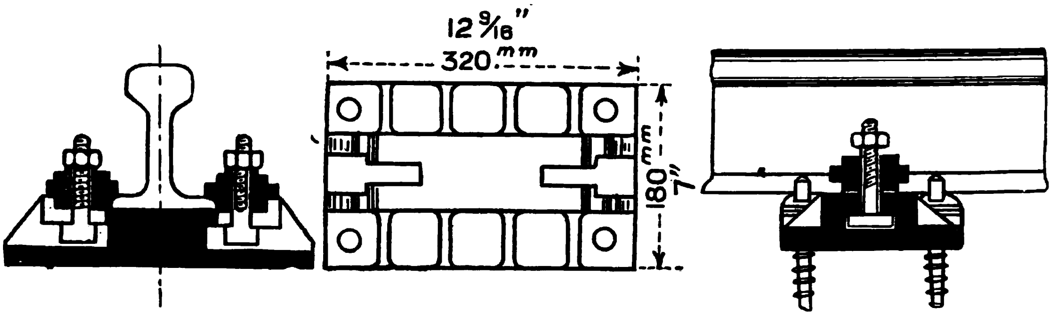


Fig. 101. — Group 1, German Experiments on Tie Plates.

washers were provided under the head of the screw spikes and the rail-fastening nut.

Eighty-three of these plates were put in service in 1898 and removed from the tracks, together with the ties, in 1907 for examination. The tie wear was found to be very slight and very uniform under the base of the plate, varying from a minimum of 0.14 millimeter ($\frac{1}{128}$ inch) to a maximum of 0.19 millimeter ($\frac{1}{160}$ inch), except in a few cases where spikes had become loose and caused an increased as well as an irregular wear.

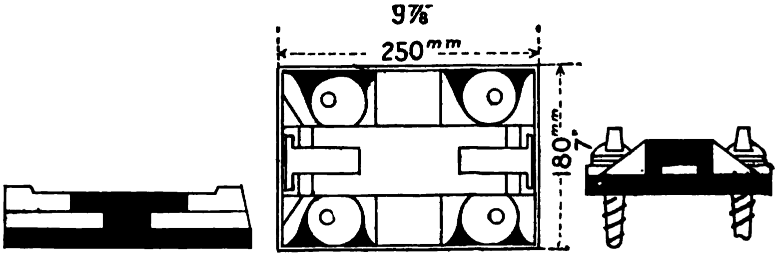


Fig. 102. — Group 2, German Experiments on Tie Plates.

Sand, however, was found between the ties and plates, and this might have caused even this slight wear. The rail seat in the tie plate had worn to about the same extent (maximum $\frac{1}{160}$ inch). No other sign of deterioration was observed.

The second series of tests, Group 2 (Fig. 102), was carried on under conditions similar to those for Group 1. The main difference between these plates

and the plates of Group 1 lies in the size of the bearing surface over tie, being about 70 square inches for Group 2 plates as against 90 square inches for Group 1 plates.

On removal of the plates, it was found that the wear of tie developed the same uniform wear as in the previous group. The slight wear gave the impression of being purely compression, there being no indication whatever of side displacement. As a matter of fact, after the screw spikes had been removed the plate had to be knocked off with a hammer. Sand was found under the edge of only a few plates. The screw spikes used on these plates were $4\frac{3}{4}$ inches by $\frac{5}{8}$ inch and had a deeper thread than those of Group 1.

In spite of the smaller bearing of this plate, as compared to Group 1, the amount of tie wear was actually smaller, and the fastening generally more satisfactory.

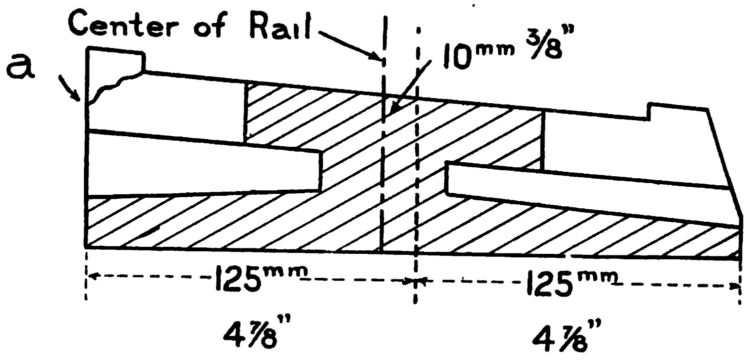


Fig. 103. — Group 3, German Experiments on Tie Plates.

Condition of test in Group 3 (Fig. 103) was similar to the previous tests in Groups 1 and 2. The main difference in this case consisted in the sloped top of the tie plate, which gave the rail a desired amount of inclination toward the gage side. This arrangement brought the center of rail closer to the outer edge of the tie plate by about 10 millimeters ($\frac{3}{8}$ inch). Screw spikes used were similar to those in Group 2, but with a somewhat better grip, the holes having been drilled smaller. To increase the rigidity of the fastening, double spring washers were employed on all the screw spikes.

The tie wear was smaller than in any previous instance. The gage of the track was measured frequently and found to remain practically unchanged. The spring washers, which had shown some failures when used singly, were found in this test to have their original elasticity unimpaired. This design of tie plate, however, failed in a few instances, as shown at "*a*," Fig. 103, which would seem to indicate that a greater stress was carried against this point than in the other arrangements.

It is clearly evident from the behavior of plates of Groups 2 and 3 that the wear of ties is not at all directly proportional to the extent of the bearing surface of the tie plate, but depends more upon the rigidity of the fastening. In the case under consideration, the most important point developed is the necessity of rigidly fastening the tie plates to the ties in order to preserve the life of the tie.

15. Fastening of the Rail to the Tie

In this country the ordinary nail spike is generally used for fastening a rail to a wooden tie. The most important objections to the spike are: first, in

Fig. 104. — Short Leaf Pine Tie, after 2 Years' Service, cut through Spike Holes. (Bureau of Forestry, Bulletin No. 50.)

the soft-wood tie the spike does not hold with sufficient firmness to keep the rail securely to the tie; second, in driving the spike into the softer woods the fibers are broken to an unusual extent (Fig. 104). As a result they do not withstand lateral pressure of the rail, and consequently the spike hole is rapidly increased to such an extent that the spike no longer holds. Water collects in the enlarged hole and decay sets in (Fig. 105).

Table XXIV * compares the holding force of a common spike (Fig. 106), weight 165 spikes to 100 pounds, with that of the common screw spike (Fig. 107), similar to those used on the French and other continental railroads, weight 85 spikes to 100 pounds.

* Holding Force of Railroad Spikes in Wooden Ties, Forest Service, Circular 46.

FIG. 105. — Cross Section through the Spike Holes of Short Leaf Pine Tie, treated with Zinc Chloride, Texas. (Bureau of Forestry, Bulletin No. 50.)

TABLE XXIV. — HOLDING FORCE OF COMMON AND SCREW SPIKES

(Forest Service, Circular 46)

Species of Wood and Kind of Spike.	Number of Tests.	Condition of Wood.	Force Required to Pull Spike.		
			Average.	Maximum.	Minimum.
			Pounds.	Pounds.	Pounds.
White oak:					
Common spike	5	Partially seasoned	6,950	7,870	6,160
Screw spike	5	do	13,026	14,940	11,050
Ratio			1.88		
Oak (probably red):					
Common spike	5	Seasoned	4,342	5,300	3,490
Screw spike	8	do	11,240	13,530	8,900
Ratio			2.61		
Loblolly pine:					
Common spike	28	Seasoned	3,670	6,000	2,320
Screw spike	20	do	7,748	14,680	4,170
Ratio			2 11		
Hardy catalpa:					
Common spike	12	Green	3,224	4,000	2,190
Screw spike	14	do	8,261	9,440	6,280
Ratio			2.56		
Common catalpa:					
Common spike	11	Green	2,887	4,500	2,240
Screw spike	11	do	6,939	8,340	5,890
Ratio			2.42		
Chestnut:					
Common spike	4	Seasoned	2,980	3,220	2,600
Screw spike	5	do	9,418	11,150	7,470
Ratio			3.15		

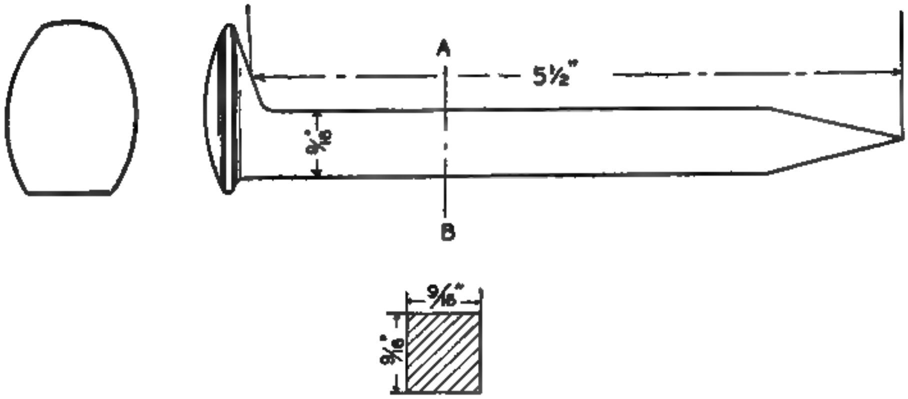


FIG. 106. — Common Spike.

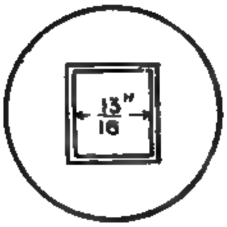


FIG. 107. — Common Screw Spike.

Tables XXV and XXVI are taken from "Studies of the Stability of Railway Tracks," by Jules Michel,* and give the holding power of hook and screw spikes.

TABLE XXV. — PULLING FORCE NECESSARY TO PULL OUT FOR 0.20 INCH IN A HOOK SPIKE AND A SCREW SPIKE BURIED 4.13 INCHES IN THE WOOD

(Jules Michel)

	P.L.M. Hook Spike.	P.L.M. Screw Spike.
	Pounds	Pounds
Poplar	992	4,454
Larch	1,598	5,291
Baltic fir, creosoted	......	5,732
Beech, treated with sulphate of copper	5,732	9,480
Oak	3,968	9,921
American cypress	5,688	6,063

Figs. 108 and 109 present examples of early screw fastenings.

FIG. 108. — Screw Spike used by Grand Duchy of Baden State Railways (1860).

* Revue Générale des Chemins de Fer, July, 1884, and June, 1893.

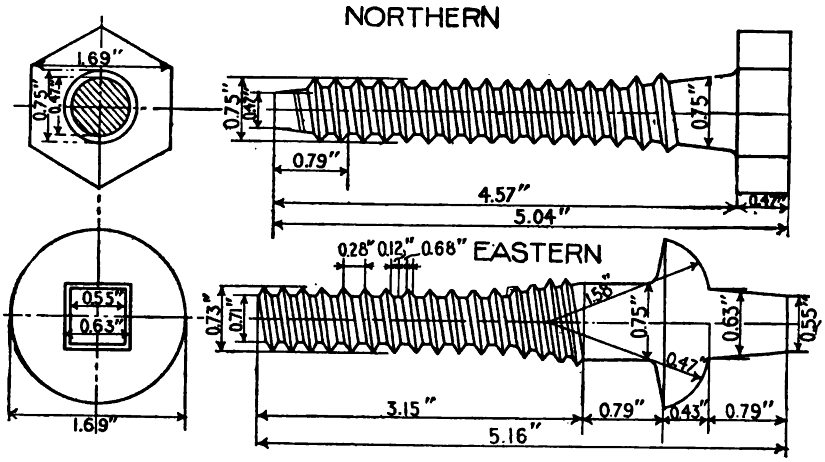


FIG. 109. — Early French Screw Spikes (1863).

TABLE XXVI. — FORCES NECESSARY FOR EXTRACTING BY 0.20-INCH SCREW SPIKES 0.79 INCH AND 0.91 INCH IN DIAMETER WITH THREADS OF 0.39-INCH AND 0.59-INCH PITCH, SUNK 4.14 INCHES IN WOOD OF VARIOUS SPECIES AND AGES

(Jules Michel)

Date of Trial.	Diameter of Screw Spike.	Pitch of Helix.	Northern Fir.	Landes Pine.	Beech.	Oak.	Diameter of Hole in Wood.	Remarks.
	Inches.	Inches.	Pounds.	Pounds.	Pounds.	Pounds.	Inches.	
				NEW WOOD CURRENTLY EMPLOYED IN TRACKS				
1875	0.79	0.39	5,733	....	9,481	9,923	0.59	See Revue Générale, July, 1884.
1881	0.79	0.39	....	....	10,143	10,584	0.59	10 trials.
1889	0.79	0.39	....	....	....	11,576	0.55	Rolled screw spikes, 24 trials.
1889	0.79	0.49	....	....	....	12,844	0.55	20 trials.
1889	0.79	0.59	....	....	....	12,458	0.55	10 trials.
1891	0.79	0.49	7,640	11,378	....	....	....	
1889	0.91	0.49	....	....	13,010	12,348	0.67	4 trials.
				WOOD HAVING BEEN 9 YEARS IN TRACK				
1889	0.79	0.39	....	....	....	10,143	0.55	10 trials.
1889	0.79	0.49	....	....	....	11,576	0.55	

Fig. 110 shows a machine used on the Atchison, Topeka and Santa Fe for preparing ties for screw spikes. Wooden dowels as shown in Fig. 111 are screwed into the ties.* Table XXVII gives the cost of equipping a mile of track with screw spikes, the estimate being based on work actually done on a section of track five miles in length on the Illinois division of the railway.

* Railroad Age Gazette, December 24, 1909.

Fig. 110. — Machine Preparing Ties for Screw Spikes. (Railroad Age Gazette.)

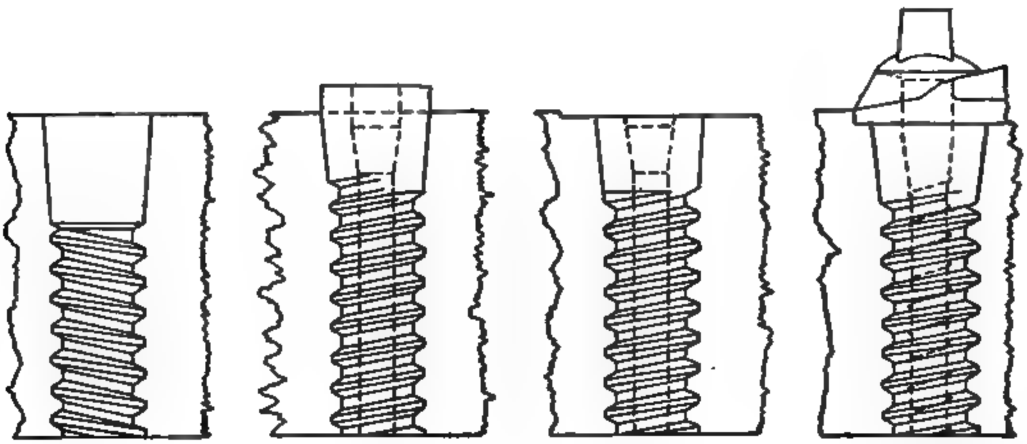


Fig. 111. — Showing Application of Screw Spike on A. T. & S. Fe R. R. (Railroad Age Gazette.)

TABLE XXVII. — ONE MILE OF TRACK WITH SCREW SPIKES AND DOWELS

12,000 spikes at 2.7 cents each	$ 324
6,000 tie plates at 21 cents each	1,260
Boring ties for, and driving, 24,000 dowels, at 1 cent each	240
24,000 wooden dowels at 1½ cents each	360
Driving screw spikes (per mile)	150
Total	$2,334

ONE MILE WITH CUT SPIKES

12,000 spikes	$ 127
6,000 tie plates at 21 cents each	1,260
Driving cut spikes (per mile)	150
Total	$1,537

* Apparently the French railways were about the first in Europe to begin the use of the screw spike (tirefond) as a rail fastening, and it is to-day universally employed by the large systems (Fig. 112, Table XXVIII).

* For a very full discussion of the subject, see "The Question of Screw Fastenings to Secure Rails to Ties," W. C. Cushing, Proceedings Am. Ry. Eng. & M. of W. Assn., 1909, Vol. 10, Part 2, p. 1456.

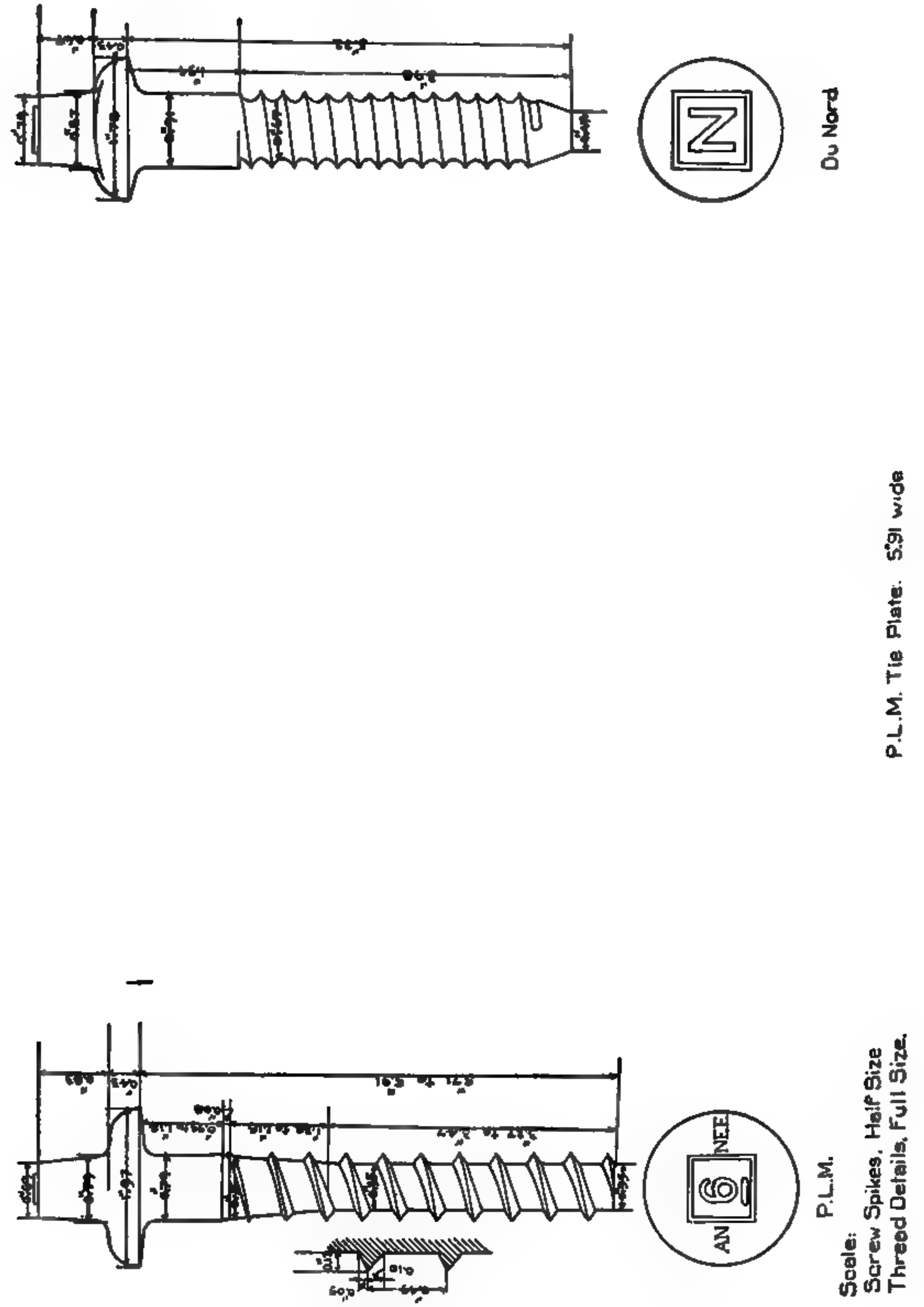


FIG. 112. — French Railways — Rail Fastenings. (Am. Ry. Eng. Assn.)

TABLE XXVIII. — FRENCH RAILWAYS — RAIL FASTENINGS

(Am. Ry. Eng. Assn.)

Railway. Name.	Miles.	Number and Position of Screw Spikes at Each End of Tie.	Type of Rail Used.	Screw Spikes. Weight in Ounces.	Length under Cap, Inches.	Diam. of Neck under Cap, Inches.	Diam. of Shank, Inches.	Pitch of Thread, Inches.	Number of Ties Used per Rail.	Joints. Arrangement.	No. of Bolts.
†De Paris à Lyon et à la Mediterranée.	6194	2 inside and 2 outside	97 lb. T.	15.52 16.22	5.71 to 5.91	0.79	0.55	0.49		Square and suspended	6
D'Orléans..........	4544	2 inside and 1 outside	*B.H.	11.62	5.71	0.87	0.59	0.39	12 to 14 per 36'	Square and suspended	4
De L'Ouest........	3631	1 inside and 1 outside 2 inside and 1 outside	T. *B.H. & T. In chairs		4.72 4.92 5.52	0.88 0.91	0.54 0.62	 0.49			
De L'Est...........	3083	2 inside and 2 outside	T.		4.73	0.91	0.65	0.49	17 per 39.37'	Square and suspended	4
Du Nord...........	2445	2 inside and 1 outside alternating with 1 inside and 2 outside	T.		4.72 to 5.32	0.91	0.67		25 per 59'	Square and suspended	4
Du Midi...........	2380	2 inside and 1 outside	*B.H.					0.31	14 to 16 per 36'	Square and suspended	4 and 6
De L'État..........	1812										

* B.H. means Bull Head.

† Mr. Cartault, Assistant Chief Engineer, says that, in oak or beech, the resistance of a screw spike to extraction reaches and often surpasses 15,432 to 17,637 pounds.

The above are all the important French railways.

TABLE XXIX. — GERMAN RAILWAYS — RAIL FASTENINGS

(Am. Ry. Eng. Assn.)

Name of State Railway.	Kind of Tie Plate.	Number and Position of Screw Spikes at Each End of Tie.	Type and Weight of Rail.	Screw Spikes. Weight in Ounces.	Length under Cap, Inches.	Diam. of Neck under Cap, Inches.	Diam. of Shank, Inches.	Pitch of Thread, Inches.	Number of Ties Used per Rail.	Joints. Arrangement.	No. of Bolts.
Württemberg.....	Hook plate. Hook outside Hook plate. Hook inside	1 inside and 2 outside 2 inside and 1 outside	T.	13.75 and 15.52	5.12 and 5.91	0.79	0.59	0.39	....	Suspended	6
Saxon............	At joints. Hook plate. Hook inside At intermediate ties	2 inside and 1 outside Hook spikes 1 inside and 2 outside	92.74 T.	14.21 and 16.15	5.32 and 6.69	0.79	0.59	0.39	....	Suspended	6
Bavarian (1).....	Hook plate. Hook inside	2 inside and 1 outside	87.7 T.	16.58	6.5	0.79	0.59	0.39	....	Suspended	4
Baden (2)........		Use hook and wedge plates and screw spikes of Bavarian State Rys.	73 T.							Suspended	4 and 6
Elsass-Lothringen	Hook plate. Hook outside	1 inside and 1 outside	91 T.	16.54	5.91	0.87	0.65	0.39	23 and 24 per 49.2'	Square and suspended	6
Prussian (3)......	Hook plate. Hook outside	2 outside and 1 inside	91 T.	16.54	5.91	0.87	0.65	0.39	19 and 24 per 49.2'	Suspended	6

(1) Use screw spikes on main tracks, and hook spikes on secondary tracks.

(2) Use steel ties almost exclusively. Use wooden ties on bridges with steel floor beams, in tunnels and for insulated joints in electric signal districts.

(3) In tunnels use cast-iron chairs, wooden wedges, spikes, and trenails identical with Midland Ry., England.

" Hook spikes are now only used on lines of minor importance."

The German railways did not adopt this style of fastening as early or as generally as those of France, and the use of the hook spike is quite widespread. In 1899, the general employment of the screw spike on all lines of the system was prescribed for the Prussian Government Railways (Fig. 113, Table XXIX).

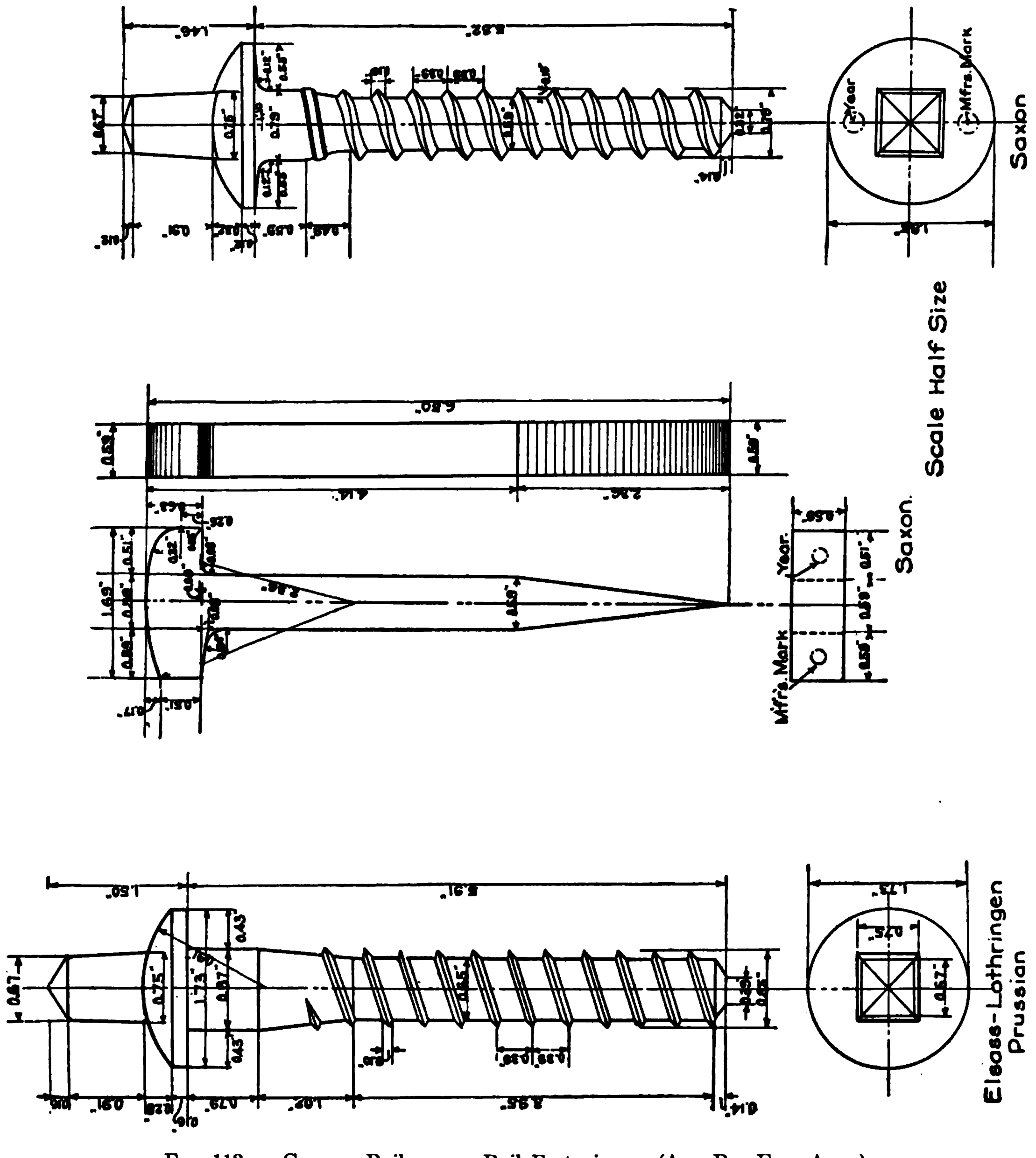


Fig. 113. — German Railways — Rail Fastenings. (Am. Ry. Eng. Assn.)
Same design of Screw Spike used by the Württemberg, Bavarian and Baden State Railways as is shown for the Saxon.

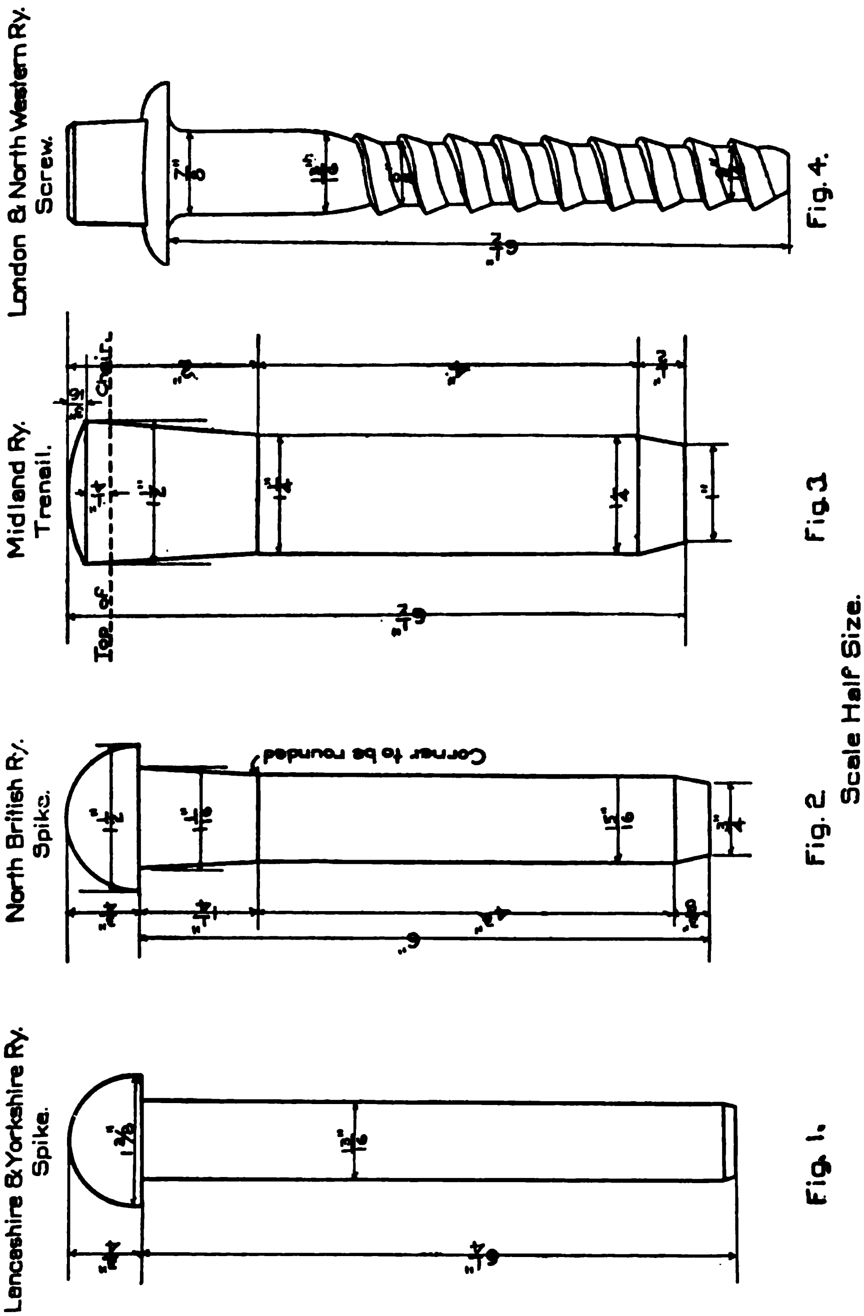


FIG. 114. — English and Scotch Railways — Rail Fastenings. (Am. Ry. Eng. Assn.)

The common hook spike used in the United States has been often severely condemned by writers in the technical press, and the readers have been usually led to infer that it is employed everywhere in Europe, which is seen from the above not to be the case. Indeed, the screw spike in Great Britain is almost as rare as it is in the United States, at least on the large systems, the only one

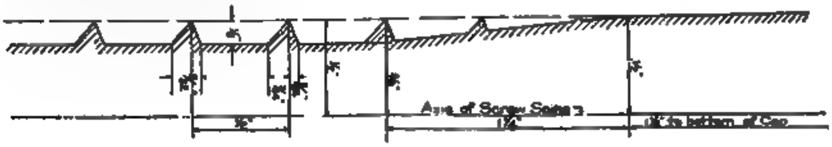
making use of it being the London and North Western, and that only partially (Fig. 114, Table XXX and Plate XIII).

All of the large railway systems in Great Britain use the double-head rail, held in position in large cast-iron chairs by wedges, and consequently the fastenings are for securing the chairs to the ties. For the purpose of fastening the chairs to the ties, the almost universal plan is to use two iron or steel spikes and two wooden trenails. The spikes are not pointed, and are driven into previously bored holes. Instead of the trenails, the London and North Western Railway makes use of two screw spikes, which resemble those of the Belgian State Railways.

TABLE XXX.—ENGLISH AND SCOTCH RAILWAYS—RAIL FASTENINGS
(Am. Ry. Eng. Assn.)

Railway.	Number and Kind of Fastenings per Chair.	Spikes.			Trenails.				
		Length under Head.	Diam. under Head.	Diam. of Shank.	Total Length.	Length of Top Cone	Top Diam	Intermediate Diam.	Diam. at Point.
		Inches.	Inches.	Inches.	Inches.	Inches.	Inches.	Inches.	Inches.
Lancashire & Yorkshire	2 spikes and 2 trenails	†6¼	⅞	⅞	§6	2	1½	1¼	1 1/16
Great Eastern	2 spikes and 2 trenails	†5¾	¾	¾	§6½	1 11/16	1½	1¼	1¼
Caledonian	4 spikes	†5¾	¾	¾					
Great Northern	*2 spikes and 2 trenails	No dimensions furnished.							
North British	*2 spikes and 2 trenails	‡6	1 1/16	⅞	§6½	2	1½	1¼	1¼
Midland	*2 spikes and 2 trenails	‡5¾	1	¾	§6½	2	1½	1¼	1¼
North Eastern	‖2 twisted spikes and 2 trenails	6	1⅛	¾	§6½	2 3/16	1½	1¼	1 3/16
Great Western	2 ⅞-inch bolts through ties	...							
London & North Western	¶2 spikes and 2 screws	¶6	13/16	13/16					

Notes. — All of these railways use bullhead rails and chairs.
* Has short mileage of chairs secured by two ⅞-inch bolts through the ties.
† Illustrated by Fig. 1 of Fig. 114.
‡ Illustrated by Fig. 2 of Fig. 114
§ Illustrated by Fig. 3 of Fig. 114.
¶ Illustrated by Fig. 4 of Fig. 114.
On the Forth Bridge the North British Ry. uses flat-bottom rails fastened to longitudinal beams by wood screws.
‖ The twisted spikes are to be abandoned for plain ones.



Actual Size

Diameter of hole required for this screw ⅝"

FIG. 115. — Screw Spike deduced from European Practice. (Cushing.)

Fig. 115 shows a design of screw spike deduced by Mr. Cushing from European practice. The form of the thread seems to have little influence upon the holding power of the screw spike. Table XXXI gives the resistance for threads of right-angle form and those of isosceles triangular form.

TABLE XXXI

RESISTANCE OF SCREW SPIKES HAVING DIFFERENT THREADS

(Jules Michel — Revue Générale des Chemins de Fer, June, 1893)

Dimensions of Screw Spikes.	Isosceles Thread.	Right-angled Thread.	Remarks.
Screw Spikes 0.79 inch in diameter. New tie.			
Pitch of 0.39 inch	11,687 pounds	12,039 pounds	Average of 4 trials.
Pitch of 0.59 inch	12,458 pounds	12,513 pounds	Average of 4 trials.
Pitch of 0.49 inch	13,010 pounds	13,561 pounds	Average of 4 trials.
Screw Spikes 0.91 inch in diameter.			
Pitch of 0.49 inch	13,424 pounds	13,424 pounds	New tie.
Screw Spike 0.79 inch in diameter.			
Pitch of 0.39 inch	10,253 pounds	9,923 pounds	Ties 9 years in service.
Pitch of 0.49 inch		11,576 pounds	Ties 9 years in service.
Screw Spikes 0.91 inch in diameter.			
Pitch of 0.49 inch	11,246 pounds	11,025 pounds	Ties 9 years in service.

The proof that the screw spike is not a thoroughly efficient rail fastening lies in the devices which have been invented to assist it in its work,—the square plug, the Collet trenail, the Thiollier helical lining, and the Lakhovsky screw and case.*

The main objection to the Collet trenail is its size; it is illustrated in Figs. 116, 117, and 118 with a screw spike and the wooden plug commonly used on French railways for repairing old holes. The difference in size is large, the Collet trenail being $1\frac{3}{4}$ inches in diameter outside the threads. This cuts away a considerable portion of the critical part of a tie, and is considered by many engineers to weaken the tie too much. The plug is only about an inch square. Nevertheless this screw dowel is largely used in Germany.

The Collet trenail has been tested from its inception by the Chemins de Fer de l'Est, but the square plug illustrated in Fig. 117 is preferred. The wooden screw, often made of elm, cannot be put in place without removing the tie from

* Lakhovsky trenail, Revue Générale des Chemins de Fer. Paris, 1909, Vol. XXXIII, pp. 324–327.

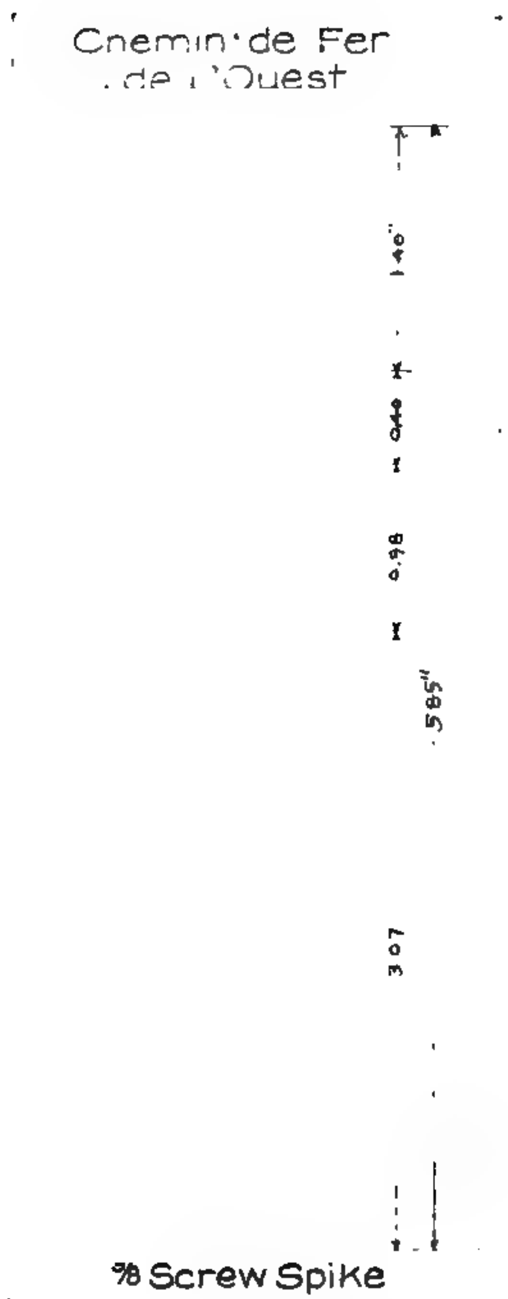


FIG. 116. — French Screw Spike.
(Am. Ry. Eng. Assn.)

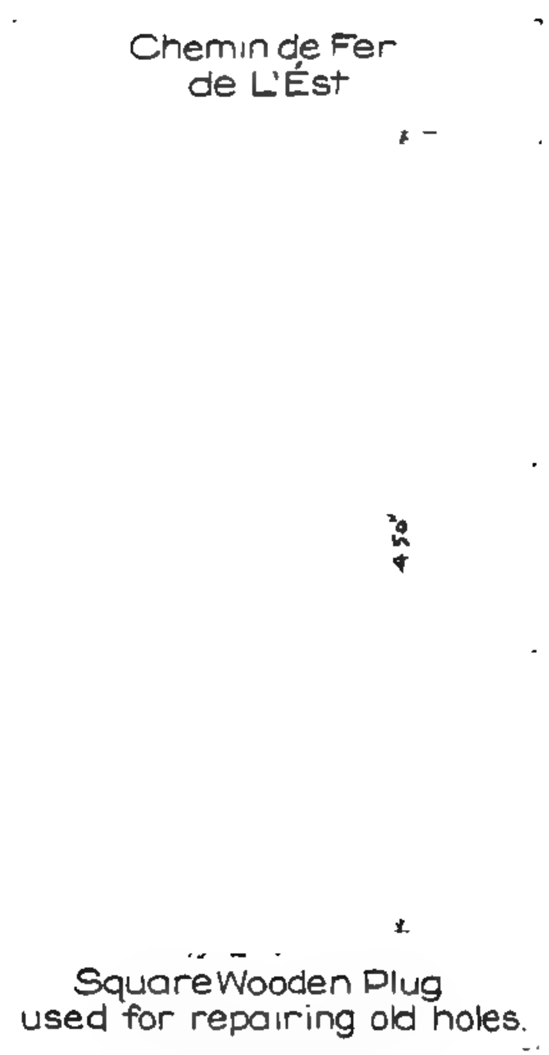


FIG. 117. — Wooden Tie Plug used on French Railways.
(Am. Ry. Eng. Assn.)

the track, and it frequently splits. The ties on the Chemins de Fer de l'Est are principally oak and beech. Figs. 119 and 120 illustrate pine ties with dowels in place.

FIG. 118. — Collet Trenail. (Am. Ry. Eng. Assn.)

The diagrams of Figs. 121 and 122 give the comparative resistance to vertical pressure of screw spikes with and without dowels.

The Thiollier steel helical lining is being experimented with as a substitute for the Collet trenail, and the Lakhovsky screw and steel casing (Bulletin of the International Railway Congress, March, 1907) are considered worth trying by the Chemins de Fer de l'Est, de l'État, and de Paris à Orléans.

From its greater holding power, the verdict of the engineers of the French, Belgian, and German railways is that the screw spike is superior to the hook spike, because they consider it very important to hold the rail fast to the tie.

On the other hand, the British railways do not seem to find the screw spike necessary for their large and heavy chairs, and they use creosoted ties, as well as the Continental lines; but the holes for their spikes are bored in advance.

According to our present knowledge, the amount of bearing surface the tie plate has upon the tie is apparently not the determining factor in providing against wear. The question of securing the plate firmly to the tie is fully as important as the size of the plate used, and in selecting a proper unit stress for the bearing on the tie it is evident, therefore, that the area of the bearing surface cannot be con-

sidered without taking account of the kind of fastening employed to hold the plate to the tie.

FIG. 119. — Cross Section of Pine Tie through Dowel. (Bureau of Forestry, Bulletin No. 50.)

FIG. 120. — Three Ties of Baltic Pine on the Prussian State Railways, Berlin, showing the manner in which screw dowels appear in the tie when ready to be shipped. (Bureau of Forestry, Bulletin No. 50.)

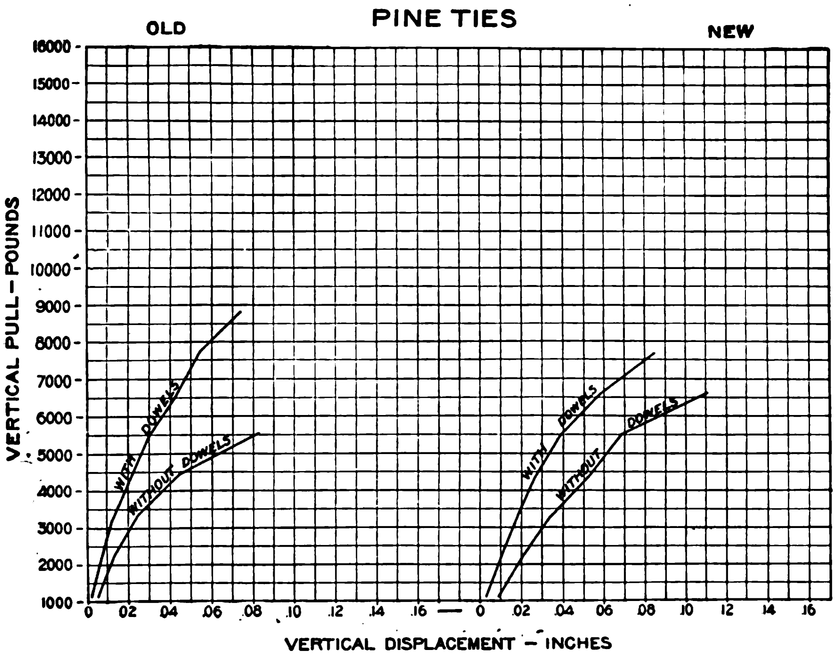


Fig. 121. — Comparative Resistance to Vertical Pressure of Screw Spikes in Pine Ties, Old and New, with and without Dowels. (Bureau of Forestry, Bulletin No. 50.)

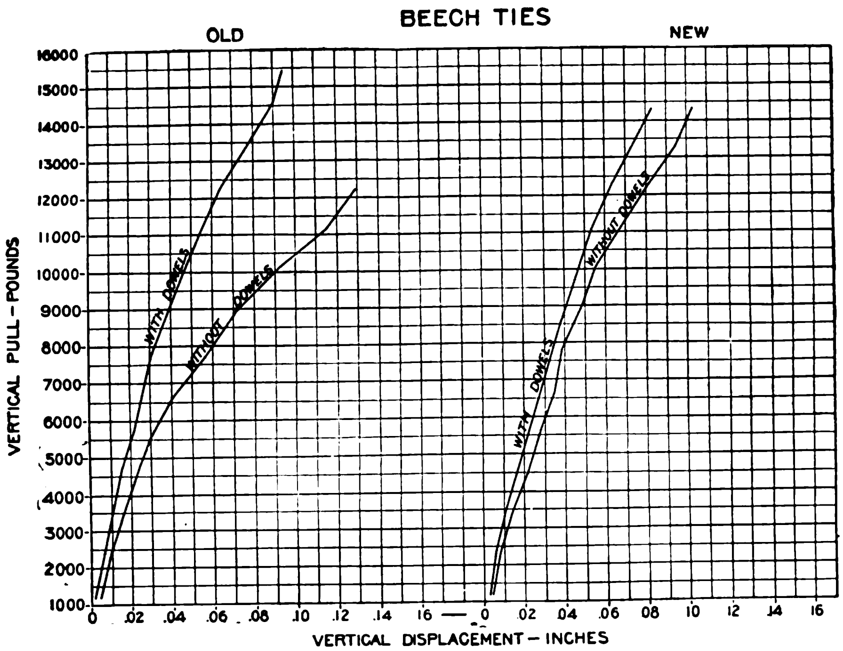


Fig. 122. — Comparative Resistance to Vertical Pressure of Screw Spikes in Beech Ties, Old and New, with and without Dowels. (Bureau of Forestry, Bulletin No. 50.)

In the case of a white-oak tie, where the spike holds well and the life of the tie is comparatively short, the ordinary working stress of the timber to resist crushing at right angles to the grain may probably be safely taken in proportioning the strength of the tie. With soft woods, however, which offer less resistance to the spike pulling loose, and which, when treated, possess long life, the ordinary working stress of the wood has little application to the bearing under the tie plate unless some means are used to secure the plate firmly to the tie.

As will be seen in the discussion of the Supporting Power of the Tie (Article 19), one of the weakest points in the support of the rail lies at the bearing of the tie plates on soft-wood ties, even when the normal crushing value of the wood is taken as is done in the calculations. It is thus of considerable importance that with a soft-wood tie a more secure fastening than the ordinary spike be used to hold the tie plate firmly to the tie.

With the increase in density of traffic there has developed a growing tendency for the rail to creep or move in the direction in which the traffic moves. On account of the joint ties being spiked through slotted holes in the joint, these ties move with the rail, with the result that correct spacing of the adjacent ties is not maintained.

To overcome this difficulty there have been devised numerous devices for anchoring the rails to the ties. These are generally fastened to the base of the rail and bear against the side of the tie; when employed in sufficient numbers they are fairly efficient in preventing the movement of the rail.*

16. Strength of the Tie

Assuming the tie to be in good condition and free from decay, we have now to determine the strength of the wood of which it is composed. Let us first examine the kinds of woods used in the United States.

* Some recent literature on this subject is as follows:

Kunze, W. — Das schienenwandern, ursache und abhilfe. 2,500 w. Ill. 1909. (In Glasers annalen für gewerbe und bauwesen, Vol. 65, p. 122.)

Considers cause of creeping in rails and devices for its prevention.

Schlüssel, L. — On the working loose of screws when used as rail fastenings, 21 p. Ill. 1907. (In Bulletin of the International Railway Congress, Vol. 21, p. 3.)

Concludes that wedge fastenings should be substituted for screw fastenings.

Tex, K. den. — Creeping of rails in the direction of the trains. 800 w. Ill. 1911. (In Bulletin of the International Railway Congress, Vol. 25, p. 292.)

Use of rail anchors. 2,000 w. Ill. 1911. (In Railway Age Gazette, Vol. 51, p. 125.)

Considers tendencies in the creeping of rails and forms of anchors most successful in overcoming it.

Wirth, Alfred. — Die schienenwanderung und ihre verhütung. 10,000 w. 1909. (In Zeitschrift des Österreichischen Ingenieur — und Architekten — Vereines, Vol. 61, p. 317, 333.)

Discussion of rail creeping at some length, considering theory and prevention by rail-fastening devices.

The following statements are based on the number of ties bought rather than on the number actually used. For all practical purposes, however, the two are identical, because the purchases in twelve months are an accurate index of consumption for a corresponding period.

Table XXXII shows the number and value of the different kinds of ties purchased by the steam and street railroad lines in the United States in 1906, and contrasts the purchases of steam railroad companies in 1905 and 1906.

TABLE XXXII. — NUMBER AND VALUE OF TIES PURCHASED BY STEAM AND STREET RAILROADS IN THE UNITED STATES IN 1905 AND 1906

(Forest Service, Circular 124)

	Steam railroads, 1905.			Steam railroads, 1906.			Street railroads, 1906.*		
	Number.	Value.	Average Value per Tie.	Number.	Value.	Average Value per Tie.	Number.	Value.	Average Value per Tie.
Oaks	34,677,304	$19,072,517	$0.55	41,532,629	$21,256,518	$0.51	3,825,245	$2,021,534	$0.53
South'rn pines†	18,351,037	7,707,436	.42	17,538,090	8,905,009	.51	1,303,120	662,736	.51
Cedar	6,962,827	3,063,644	.44	6,416,867	3,044,446	.47	666,575	265,670	.40
Douglas fir	3,633,276	1,198,981	.33	6,706,222	2,782,967	.41	542,340	227,425	.42
Chestnut	4,717,604	2,264,450	.48	4,646,763	2,132,984	.46	1,942,212	862,958	.44
Cypress	3,483,746	1,149,636	.33	4,988,585	1,813,500	.36	115,911	48,635	.42
Western pine	(‡)	....	.....	3,909,500	1,673,359	.43	60,105	24,668	.41
Tamarack	3,060,082	1,101,630	.36	2,430,236	837,217	.34	146,623	52,344	.36
Hemlock	1,713,090	565,320	.33	2,037,002	576,896	.28	21,196	6,072	.29
Redwood	590,852	118,170	.20	725,346	248,844	.34	523,283	287,328	.55
Lodgepole pine	(‡)	....	.....	553,838	210,458	.38	900	360	.40
White pine	(‡)	....	.....	258,030	76,833	.30	115,357	74,219	.64
All others	791,409	343,662	.43	1,734,517	661,501	.38	93,550	64,643	.69
Total	77,981,227	$36,585,446	$0.47	93,477,625	$44,220,532	$0.47	9,356,417	$4,598,592	$0 49

* No figures for street railroads in 1905.
† For 1905 includes white pine, lodgepole pine, and western pine.
‡ Included in southern pines.

The purchases of ties reported by the steam railroad companies in 1906 exceeded those of 1905 by more than 15,000,000. Nearly one-half of this excess was oak. The purchases of cedar ties showed a decrease of about one-half million, due possibly to the sharp demand for cedar poles, which operated against the production of ties. Douglas fir ties nearly doubled in quantity, and both cypress and hemlock increased by a large percentage, but tamarack purchases fell off more than one-fifth and chestnut about 1.5 per cent.

Oak, the chief wood used for ties, furnishes more than 44 per cent, nearly one-half of the whole number, while the southern pines, which rank second, contribute about one-sixth. Douglas fir and cedar, the next two, with approximately equal quantities, supply less than one-fifteenth apiece. Chestnut, cypress, western pine, tamarack, hemlock, and redwood are all of importance, but no one of them furnishes more than a small proportion.

Table XXXIII shows, by kinds, the number and cost of the cross-ties purchased by steam and electric railroads in the United States in 1907.

Table XXXIV gives a comparative statement showing the number of cross-ties purchased by the steam and electric railroads during the years 1910, 1909, 1908, and 1907.

Of the total purchases of cross-ties during 1910, 139,596,000, or 94.2 per cent, were made by steam railroads, while electric railroads purchased 8,635,000, or 5.8 per cent. The steady increase in the number of cross-ties reported as purchased for new track is noteworthy. The total for this purpose in 1910 was 22,255,000, as against 16,437,000 in 1909, 7,431,000 in 1908, and 23,557,000 in 1907; the total for 1910 exceeding that for 1909 by 35.4 per cent, for 1908 by 199.5 per cent, and nearly equaling that for 1907, the largest ever recorded. Largely as a logical result of the greater demand for cross-ties during 1910, the average cost per tie at point of purchase advanced to 51 cents, the same figure reached in 1907, as compared with 49 cents in 1909 and 50 cents in 1908.

In 1910, as in preceding years, oak was the principal kind of wood used for cross-ties. The number of oak cross-ties formed 46.1 per cent of the total for 1910, as compared with 46.2 per cent in 1909, 42.8 per cent in 1908, and 40.2 per cent in 1907.

A substantial increase in 1910 over 1909 is shown in the number of southern pine cross-ties reported; the increase in the cut from this species over 1909 being 22.8 per cent, as against an increase of 20 per cent in the total number of cross-ties reported from all woods. Douglas fir also showed for 1910 over the preceding year a larger increase, namely, 28.2 per cent, than the increase in the total purchase from all woods. On the other hand, chestnut, cedar, and cypress, with increases over 1909 of 17.1 per cent, 7.8 per cent, and 17.6 per cent, respectively, were bought in relatively smaller quantities.

While the bulk of the cross-ties were cut from the six woods mentioned during each of the four years and while combined they contributed 85.5 per cent of the total in 1910, 85.3 per cent in 1909, 86.5 per cent in 1908, and 87.2 per cent in 1907, a remarkable and significant showing in connection with the figures for 1910 is noted with reference to certain woods which hitherto have been utilized as cross-tie material to only a very limited extent. The increase in the number of cross-ties over 1909, reported as cut from elm, was 451.7 per cent; gum, 328.8 per cent; birch, 323.3 per cent; spruce, 121.5 per cent; and mesquite, 114.9 per cent. A very large percentage of the cross-ties cut from these woods were given some preservative treatment, thus increasing their life to or beyond that of untreated cross-ties made from the more commonly used or standard cross-tie

TABLE XXXIII. — CROSS-TIES PURCHASED BY STEAM AND ELECTRIC ROADS OF THE UNITED STATES IN 1907

(Bureau of the Census, Forest Products No. 8)

Kind.	Total.			Steam Railroads.					
				Hewed.			Sawed.		
	Number.	Total Cost.	Average Cost per Tie.	Number.	Total Cost.	Average Cost per Tie.	Number.	Total Cost.	Average Cost per Tie.
Total. .	153,699,620	$78.958,695	$0.51	112,309,246	$56,522,768	$0 50	31,776,434	$17,020,882	$0 54
Oaks... .	61,757,418	32.985,122	0 53	51,169,478	26,774,251	0.52	6,929,572	4,033,150	0 58
Southern pines	34,215,081	18,434,198	0 54	25,629,749	13,100,589	0.51	7,415,686	4,569,060	0 62
Douglas fir...	14,524,266	6,818,869	0 47	1,436,258	590,754	0 41	12,366,640	5,884,822	0 48
Cedar........	8,953,205	4,473,960	0 50	7,941,152	3,987,035	0.50	396,891	190,322	0.48
Chestnut.....	7,851,325	3,772,048	0.48	4,922,831	2,337,697	0.47	889,420	426,523	0 48
Cypress.	6,778,944	3,099,439	0.46	5,695,640	2,552,381	0 45	884,915	453,058	0 51
Western pine..	5,019,247	2,515.798	0 50	3,206,754	1,576,457	0 49	1,626,330	835,895	0 51
Tamarack....	4,562,190	2,254,617	0 49	4,144,127	2.083,646	0 50	340,618	137,481	0 40
Hemlock.....	2,366,459	807,241	0 34	2,283,675	770,969	0.34	79,256	34,796	0.44
Redwood.....	2,030,982	1,198,497	0.59	884,552	507,154	0 57	406,519	224,525	0 55
Lodgepole pine	666,916	332,984	0 50	666,916	332,984	0.50	.	. . ....	.
White pine....	474,455	193,606	0 41	289,624	106,528	0 37	131,671	53,041	0 40
All other.....	4,499,132	2,072,316	0 46	4,038,490	1,802,323	0 44	308,916	178,209	0.58

TABLE XXXIV. — CROSS-TIES PURCHASED BY STEAM AND ELECTRIC ROADS OF THE UNITED STATES DURING THE YEARS 1910, 1909, 1908, AND 1907

(Bureau of the Census)

Kind of Wood.	1910		1909		1908		1907	
	Number.	Cost at point of purchase.	Number.	Cost at point of purchase.	Number.	Cost at point of purchase.	Number.	Cost at point of purchase.
Total . .	148,231,000	$75,889,000	123,751,000	$60,321,000	112,467,000	$56,282,000	153,703,000	$78,959,000
Oak	[illegible]		57,132,000	29,062,000	48,110,000	24,653,000	61,757,000	32,984,000
Southern pine . .	[illegible]		21,385,000	11,112,000	21,530,000	11,590,000	34,215,000	18,434,000
Douglas fir....... . .	[illegible]		9,067,000	3,754,000	7,988,000	3,590,000	14,525,000	6,819,000
Chestnut	[illegible]		6,629,000	2,947,000	8,074,000	3,982,000	7,851,000	3,773,000
Cedar	[illegible]		6,777,000	3,085,000	8,172,000	4,028,000	8,954,000	4,474,000
Cypress . . .	[illegible]		4,589,000	1,002,000	3,457,000	1,520,000	6,780,000	3,099,000
Tamarack	[illegible]		3,311,000	1,356,000	4,025,000	2,019,000	4,562,000	2,254,000
Western pine . ..	[illegible]		6,797,000	3,619,000	3,003,000	1,573,000	5,019,000	2,516,000
Hemlock	[illegible]		2,642,000	865,000	3,120,000	1,179,000	2,367,000	807,000
Redwood	[illegible]		2,088,000	1,108,000	871,000	444,000	2,032,000	1,199,000
Gum	1,821,000		378,000	198,000	262,000	117,000	15,000	4.000
Beech	798,000		195,000	69,000	192,000	86,000	52,000	21,000
Maple	773,000		158,000	55,000	151,000	68,000	.	.. . .
Elm	548,000	[illegible]	99,000	46,000	65,000	24,000		.
Spruce	499,000	251,000	225,000	109,000	141,000	66,000	104,000	41,000
White pine	429,000	201,000	556,000	237,000	707,000	335,000	475,000	194,000
Birch	393,000	170,000	92,000	32,000	111,000	38,000	.	.
Lodgepole pine	238,000	121,000	487,000	224,000	518,000	247,000	667,000	333,000
Hawaiian Ohia ..	178,000	156,000	120,000	117,000	.		. .	
Mesquite .. .	134,000	71,000	62,000	39,000	34,000	21,000	.	
All other	476,000	266,000	962,000	385,000	1,846,000	684,000	4,328,000	2,007,000

woods. The growing scarcity of these last-mentioned woods, however, tends to increase their cost and accounts largely for the introduction of substitutes cut from cheaper species. The drift in this direction is clearly brought out by a comparison of the figures relating to treated cross-ties during the past four years. In 1907 the number of cross-ties reported as having been given some preservative treatment was 19,856,000; in 1908, 23,776,000; in 1909, 22,033,00; and in 1910, 30,544,000; the number for 1910 showing an increase over that for the preceding year of 8,511,000, or nearly 39 per cent.

The question of tie preservation is becoming more and more important as the demand for tie material increases and the traffic requirements become more exacting. So long as plenty of white-oak ties could be secured, the necessity for tie preservation was not felt; but with the constantly increasing use of pine and other less decay-resistant woods, it has become a vital economic question. The railroad companies have met the problem by establishing treating plants in various parts of the United States and by laying experimental tracks with treated ties to determine the efficiency of the several preservatives under varying conditions.*

Table XXXV, prepared by the Forest Service,† gives the results of an elaborate series of tests upon the strength of treated and untreated pine ties.

In outlining the plan for these tests two divisions were made, dealing respectively with the effect on the strength of timber of the preliminary processes of steaming, superheating, vacuum, etc., commonly employed in the preservation of wood, and the effect of the preserving materials themselves. The tests were confined to sapwood, and were made on small pieces taken from the tie, and also on full-sized ties.

The effect of the preliminary processes was determined on both green and seasoned timber. Both green and seasoned timber were also used in determining the effect of preservatives. The preservative fluids included only creosote ‡ and zinc chloride.

The material for the experiments was railroad ties 11 feet long. One 8-foot section of each tie was put through the particular treatment, and the untreated section, 3 feet long, was used for control test pieces.

From each tie 12 pieces were taken, 4 from the control section and 8 from the treated section. All of these pieces were 2 inches by 2 inches in cross section and 36 inches long, with one side parallel to the direction of the annual rings

* Experiments with Railway Cross-ties, Forest Service, Circular 146.

† Experiments on the Strength of Treated Timber, Forest Service, Circular 39, by W. K. Hatt.

‡ The treatment was essentially the "Rueping" process, although this name is not used in the circular.

TABLE XXXV. — EXPERIMENTS ON THE STRENGTH OF TREATED TIMBER

(Forest Service, Circular 39)

EFFECT OF STEAMING AND PRESERVATIVE TREATMENTS ON THE STRENGTH OF GREEN LOBLOLLY PINE

[Specimens, 2 by 2 inches; air-dried before tests]

Treatment.	Cylinder Conditions. Steaming. Period.	Cylinder Conditions. Steaming. Pressure.	Cylinder Conditions. Steaming. Temperature.	Cylinder Conditions. Absorption of Preservative.	Strength. Static. Bending — Modulus of Rupture.	Strength. Static. Compression Parallel to Grain.	Strength. Impact. Bending — Height of Drop Causing Complete Failure.	Strength. Average of the Three Strengths.	Rings per Inch. Control.	Rings per Inch. Treated.	Moisture. Control.	Moisture. Treated.	Specific Gravity (dry). Control.	Specific Gravity (dry). Treated.
	Hrs.	Lbs. per sq. in.	°F.	Lbs. per cu. ft.	Per cent.	Per cent.	Per cent.	Per cent.			Per cent.	Per cent.		
					Untreated wood = 100 per cent.									
Steam, at various pressures	4	20	257	....	92.8	93.1	93.8	93.2	7.5	6.5	13.8	13.4	0.558	0.546
	4	30	273	....	99.8	104.3	102.0	102.0	7.5	7.0	12.7	12.2	.553	.571
	4	40	287	....	94.6	99.0	107.7	100.4	6.0	6.0	13.6	12.4	.525	.534
	4	50	296	....	94.5	96.4	103.5	98.1	6.5	6.5	13.7	12.5	.514	.508
					Steamed wood = 100 per cent.									
Creosote, injected at 150°F. under a pressure of 100 pounds per square inch...	4	20	258	25.4	81.6	79.9	102.4	88.0	6.5	6.0	13.2	....	.553	.....
Zinc chloride:														
2.5 per cent solution...	4	20	249	....	87.4	92.8	113.8	98.0	6.5	6.0	12.8	13.7	.530	.534
3.5 per cent solution...	4	20	246	....	97.4	95.2	92.7	95.1	7.5	7.0	13.1	13.5	.538	.539
5.0 per cent solution...	4	20	246	....	99.8	96.7	78.9	91.8	5.5	6.0	12.3	13.4	.510	.506
10.0 per cent solution...	4	20	255	....	100.1	100.4	74.8	91.8	8.5	8.5	13.2	13.5	.582	.612

PHYSICAL CHARACTERISTICS AND AVERAGE STRENGTHS OF THE AIR-DRIED UNTREATED WOOD

Moisture..	per cent	13.4
Weight per cubic foot (dry)..	pounds	33.6
Rings per inch..		7
Modulus of elasticity..............................	pounds per square inch	1,893,000
Bending strength at elastic limit....................	" " "	6,998
Bending strength at rupture.........................	" " "	13,198
Compression strength parallel to grain..............	" " "	6,555
Compression strength at right angles to grain.......	" " "	834
Shearing strength radial to grain..................	" " "	1,145

TABLE XXXV. — *Continued*

EFFECT OF STEAMING AND PRESERVATIVE TREATMENTS ON THE STRENGTH OF SEASONED LOBLOLLY PINE

[Specimens, full-sized ties; seasoned, treated, and reseasoned before tests]

Treatment.	Cylinder Conditions.			Strength (static).				Spike Pulling.		Rings per Inch.	Weight, Air-seasoned.
	Steaming.			Bending	Compression.		Average of the Three Strengths.	Force Required to Pull Spike.			
	Period.	Pressure.	Temperature.	Modulus of Rupture.	Parallel to Grain.	At Right Angles to Grain.		Screw.	Common.		
	Hrs.	Lbs. per sq. in.	°F.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.		Lbs. per cu. ft.
				Untreated wood = 100 per cent.							
Steam, at various pressures	4	10	237	99.2	79.3	91.1	89.9	118.5	110.7	4.9	38.0
	4	20	258	93.7	78.4	99.1	90.4	103.6	109.4	5.2	37.3
	4	30	274	87.8	83.4	92.7	88.0	100.1	96.5	5.3	37.9
	4	40	286	88.4	78.1	74.6	80.4	93.0	77.9	5.2	37.8
	4	50	295	69.1	60.6	74.4	68.0	80.4	70.3	4.8	36.1
Steam, for various periods	2	20	257	82.4	81.9	87.1	83.8	97.9	93.7	5.1	38.1
	4	20	258	93.7	78.4	99.1	90.4	103.6	109.4	5.2	37.3
	6	20	256	87.5	78.8	92.0	86.1	83.0	79.0	4.6	36.7
	10	20	256	77.0	75.5	73.2	75.2	84.1	76.8	4.8	36.7
Zinc chloride, 2.5 per cent solution	4	20	258	74.7	65.1	68.6	69.5	75.3	73.8	4.3	41.5
Creosote, 28 pounds per cubic foot	4	20	257	69.5	61.2	60.1	63.6	68.2	68.1	4.6	65.3

PHYSICAL CHARACTERISTICS AND AVERAGE STRENGTHS OF THE UNTREATED WOOD

Moisture	per cent (approximate)	20.0
Weight per cubic foot (air-seasoned)	pounds	38.4
Rings per inch		5
Modulus of elasticity	pounds per square inch	1,568,000
Bending strength at elastic limit	" " "	3,429
Bending strength at rupture	" " "	6,458
Compression strength parallel to grain	" " "	4,452
Compression strength at right angles to grain (rail-bearing)	" " "	503
Spike pulling — common spike	" " "	3,598
Spike pulling — screw spike	" " "	7,748

TABLE XXXV. — *Continued*

EFFECT OF STEAM AND CREOSOTE ON THE STRENGTH OF SEASONED LOBLOLLY PINE

[Specimens, 2 by 2 inches; tested immediately after treatment]

Treatment.	Cylinder Conditions. Steaming. Period.	Steaming. Pressure.	Steaming. Temperature.	Absorption of Preservative.	Strength. Static. Bending — Modulus of Rupture.	Static. Compression Parallel to Grain.	Impact. Bending — Height of Drop Causing Complete Failure.	Average of the Three Strengths.	Rings per Inch. Control.	Rings per Inch. Treated.	Moisture. Control.	Moisture. Treated.	Specific Gravity (dry). Control.	Specific Gravity (dry). Treated.
	Hrs.	Lbs. per sq. in.	°F.	Lbs. per cu. ft.	Per cent.	Per cent.	Per cent.	Per cent.			Per cent.	Per cent.		
					Seasoned wood = 100 per cent.									
Steam, at various pressures	4	.....	212	.....	92.6	106.4	124.0	107.7	6.0	5.0	20.4	23.1	0.464	0.476
	4	50	291	.....	70.9	55.1	72.9	66.3	6.0	6.5	19.0	28.3	.513	.502
					Steamed wood = 100 per cent.									
Creosote, injected at 150° F. under a pressure of 100 pounds per square inch...	4	20	252	25.62	97.1	102.2	110.7	103.3	7.0	6.5	21.6	....	.541	.....
					Seasoned wood = 100 per cent.									
	...	......	...	21.18	81.0	78.4	82.0	80.4	7.5	7.0	18.9	....	.553	.....
					Soaked untreated wood = 100 per cent.									
Soaking, wood previously treated with creosote injected at 150° F. under a pressure of 100 pounds per square inch.............	...	......	...	19.20	139.4	160.4	.....	.....	6.0	6.5	78.1	....	.512	.....

PHYSICAL CHARACTERISTICS AND AVERAGE STRENGTHS OF THE UNTREATED SEASONED WOOD

Moisture...	per cent	19.7
Weight per cubic foot (dry)...	pounds	30.48
Rings per inch..		6
Modulus of elasticity..................................	pounds per square inch	1,609,000
Bending strength at elastic limit..........................	" " "	5,636
Bending strength at rupture..............................	" " "	9,444
Compression strength parallel to grain..................	" " "	4,819
Compression strength at right angles to grain............	" " "	539
Shearing strength radial to grain.......................	" " "	1,069

TABLE XXXV. — *Concluded*

EFFECT OF CREOSOTING WITHOUT STEAM ON THE STRENGTH OF SEASONED LOBLOLLY PINE

[Specimens, 2 by 2 inches; seasoned, treated, and air-dried before tests]

Treatment.	Strength (static). Bending — Modulus of Rupture.	Strength (static). Compression Parallel to Grain.	Rings per Inch. Control.	Rings per Inch. Treated.	Moisture Control.	Weight (air-seasoned). Control.	Weight (air-seasoned). Treated.
	Per cent.	Per cent.			Per cent.	Lbs. per cu. ft.	Lbs. per cu. ft.
	Untreated wood = 100 per cent.						
Creosote....................	117.0	130.0	5	7	16.1	34.79	38.28

PHYSICAL CHARACTERISTICS AND AVERAGE STRENGTHS OF THE UNTREATED WOOD

Moisture...	per cent	16.1
Weight per cubic foot (dry)...	pounds	30
Rings per inch..		5
Modulus of elasticity..................................	pounds per square inch	1,356,000
Bending strength at elastic limit..........................	" " "	4,439
Bending strength at rupture..............................	" " "	8,760
Compression strength parallel to grain..................	" " "	4,956
Compression strength at right angles to grain............	" " "	700
Shearing strength radial to grain.......................	" " "	1,105

and the other at right angles to it. After the bending tests had been made on these pieces, smaller pieces, 2 inches by 2 inches in cross section and 4 inches long, were cut from their ends and used for the compression and shearing tests. In any tie the test pieces were taken out according to Fig. 123, variation being allowed only to secure clear pieces.

The test pieces from each tie were marked consecutively from 1 to 12. The untreated pieces, marked 1 and 2, were used for control-impact tests, and those marked 3 and 4 for control-static tests. The treated pieces, marked 5 and 6, were used for impact tests; those marked 7 and 8 for static tests. The

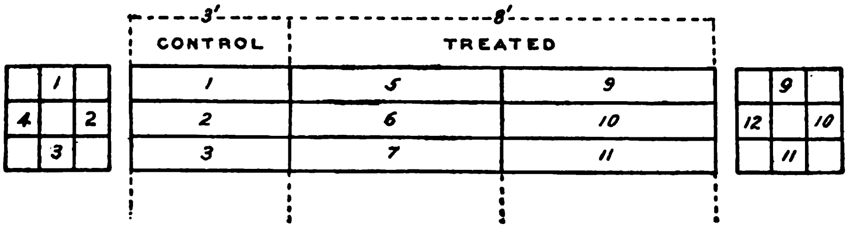


Fig. 123. — Control Plan — Creosote Tie Tests.

treated pieces, marked from 9 to 12, were similarly tested, but were resoaked, if necessary, to bring them back to the degree of moisture found in the control pieces. Ordinarily the steaming process did not decrease the moisture content of the wood, in which case tests on resoaked pieces were not required.

In addition to the tests on small pieces, the strength of full-sized ties in bending and in compression, both parallel and at right angles to grain, was obtained, as well as the capacity of the wood to hold a spike. The ties used were 8 feet long. The entire tie was treated and afterwards tested in full size. In the bending tests under a static load, the ties were supported on a span of 80 inches and loaded at the third points of the span.

Short sections of the ties were used for tests to determine the resistance against compression parallel to grain, against compression at right angles to grain (which is similar to that produced on a tie by the base of a rail), and against the force withdrawing a spike. In the tests of compression at right angles to grain, the width of the tool equaled that of the base of an 80-pound A. S. C. E. rail. The force necessary to cause the yielding of the wood was measured. Both screw spikes and common spikes were driven into the tie, and the force necessary to pull them out directly along their length was measured. Any common spike was driven but once, since it was found that the resistance against pulling diminished when the spike was redriven into new wood.

The weight of the tie before treating, after treating, and at the time of test was determined. The physical characteristics of the wood, such as per

cent of sap, rate of growth, shakes, knots, and moisture content, were also recorded.

Impact tests were made on certain of the full-sized ties. In general, it was found that the influence of the various factors may be determined by both static and impact tests.

The results of these tests form a body of evidence from which the following general conclusions may be drawn:

(1) A high degree of steaming is injurious to wood in strength and spike-holding power. The degree of steaming at which pronounced harm results will depend upon the quality of the wood and its degree of seasoning, and upon the pressure (temperature) of steam and the duration of its application. For loblolly pine the limit of safety is certainly 30 pounds for 4 hours, or 20 pounds for 6 hours.

(2) The presence of zinc chloride will not weaken wood under static loading, although the indications are that the wood becomes brittle under impact when treated with solutions above 3.5 per cent concentration.

(3) A light treatment with creosote will not weaken wood of itself. Since, apparently, it is present only in the openings of the cells, and does not get into the cell walls, its action can only be to retard the seasoning of the wood.

The Committee on Wood Preservation of the American Railway Engineering Association in its report at the March, 1910, Convention of the Association presented the following conclusions based on the best data available at the time on the strength of treated timber:

(*a*) High steaming will diminish the strength rapidly.

(*b*) Treating with strong solution of zinc chloride will render the timber brittle, perhaps because of free acid in the solution.

(*c*) Creosote is inert.

(*d*) Seasoned timber treated with light doses of creosote is as strong as the original timber.

Tables XXXVII and XXXVIII give the results of tests of the Forest Service on a number of woods, and Table XXXIX shows the unit stresses recommended by the Committee on Wooden Bridges and Trestles of the American Railway Engineering Association.

The great variation in strength, which is noticeable in timber of the same species, makes it necessary to accept with caution the result of a limited number of tests representing the average of the species. One of the most troublesome factors influencing the strength of wood is the amount of moisture in it.

TABLE XXXVI. — ACCOUNT OF TEST MATERIAL USED IN TABLE XXXVII

SUMMARY OF MECHANICAL TESTS ON THIRTY-TWO SPECIES OF AMERICAN WOODS

(Division of Forestry, Circular 15)

No.	Name of Species.	Number of Trees.	Number of Mechanical Tests.	Average Specific Gravity of Dry Wood.	Localities and Number of Trees from Each.
1	Longleaf pine. (Pinus palustris.)	68	6,478	0.61	Alabama, coast plain (22); uplands (6); hill district (6); Georgia, undulating uplands (6), South Carolina, coast plain (7); Mississippi, low coast plain (2); Louisiana, low coast plain, gravelly soil (7); sandy loam (6); Texas, low coast plain (6).
2	Cuban pine (Pinus heterophylla.)	12	2,113	.63	Alabama, coast plain (6); Georgia, uplands (1); South Carolina, coast (5).
3	Shortleaf pine (Pinus echinata.)	22	1,831	.51	Alabama, uplands (4); Missouri, low hilly uplands (6); Arkansas, low hilly uplands (6); Texas, uplands (6).
4	Loblolly pine (Pinus tæda).	32	3,335	.53	Alabama, mountainous plateau (8); low coast plain (6); Arkansas, level flood plain (5); Georgia, level coast plain (6); South Carolina, low coast plain (7).
5	White pine (Pinus strobus.)	17	540	.38	Wisconsin, clay, uplands (5); sandy soils (4); sandy loam (5); Michigan, level drift lands (3).
6	Red pine (Pinus resinosa.)	8	412	.50	Wisconsin, drift (5); Michigan (3).
7	Spruce pine (Pinus glabra.)	4	696	.44	Alabama, low coast plain.
8	Bald cypress (Taxodium distichum.)	20	3,396	.46	South Carolina, pine barren (6); river bottom (4); Louisiana, coast plain, border of lake (4); Mississippi, Yazoo bottom (3); upland (3).
9	White cedar (Chamæcyparis thyoides.)	4	354	.37	Mississippi, low plain.
10	Douglas spruce (Pseudotsuga taxifolia.)	....	225	.51	(From lumber yard.)
11	White oak (Quercus alba.)	12	1,009	.80	Alabama, ridges of Tennessee Valley (5); Mississippi, low plain (7).
12	Overcup oak (Quercus lyrata.)	10	911	.74	Mississippi, low plain (7); Arkansas, Mississippi bottoms (3).
13	Post oak (Quercus minor.)	8	256	.80	Alabama, Tennessee Valley (5); Arkansas, Mississippi bottom (3).
14	Cow oak (Quercus michauxii.)	11	935	.74	Alabama, Tennessee Valley (4); Arkansas, Mississippi bottoms (3); Mississippi, low plain (4).
15	Red oak (Quercus rubra.)	7	299	.73	Alabama, Tennessee Valley (5); Arkansas, Mississippi bottom (2).*
16	Texan oak (Quercus texana.)	3	479	.73	Arkansas, Mississippi bottom.
17	Yellow oak (Quercus velutina.)	5	222	.72	Alabama, Tennessee Valley (5).
18	Water oak (Quercus nigra.)	4	132	.73	Mississippi, low plain (4).
19	Willow oak (Quercus phellos.)	12	649	.72	Alabama, Tennessee Valley (5); Arkansas, Mississippi bottom (3); Mississippi low plain (4).
20	Spanish oak (Quercus digitata.)	11	1,035	.73	Alabama, Tennessee Valley (5); Arkansas, Mississippi bottom (3); Mississippi, low plain (3).
21	Shagbark hickory (Hicoria ovata.)	6	794	.81	Mississippi, alluvial plain (3); limestone (3).
22	Mockernut hickory (Hicoria alba.)	4	300	.85	Mississippi, low plain.
23	Water hickory (Hicoria aquatica.)	2	197	.73	" "
24	Bitternut hickory (Hicoria minima.)	4	100	.77	" "
25	Nutmeg hickory (Hicoria myristicæformis.)	3	294	.78	" "
26	Pecan hickory (Hicoria pecan.)	2	172	.78	" "
27	Pignut hickory (Hicoria glabra.)	3	84	.89	" "
28	White elm (Ulmus americana.)	2	91	.54	Mississippi, bottom.
29	Cedar elm (Ulmus crassifolia.)	3	201	.74	Arkansas, bottom.
30	White ash (Fraxinus americana.)	3	476	.62	Mississippi, bottom.
31	Green ash (Fraxinus lanceolata.)	1	45	.62	" "
32	Sweet gum (Liquidambar styraciflua.)	7	508	.59	Arkansas, bottom (3); Mississippi, low plain (4).

* These two should probably be classed as Southern red oak. They were collected before the distinction was finally decided upon.

Note. — The values for specific gravity here given refer to "dry" wood of test material, *i.e.*, wood containing variable amounts of moisture below 15 per cent; the moisture effect has therefore not been taken into account, but more careful experiments indicate that its influence on specific gravity at such low per cent is so small that it may be neglected for practical purposes.

In Table XXXVII all values except those for the Southern pines have been referred to 12 per cent moisture, which may be said to be the lightest average moisture content of seasoned wood.

TABLE XXXVII. — RESULTS OF TESTS IN BENDING — AT RUPTURE

SUMMARY OF MECHANICAL TESTS ON THIRTY-TWO SPECIES OF AMERICAN WOODS

(Division of Forestry, Circular 15)

[Pounds per square inch]

No.	Species.	Number of Tests.	Highest Single Test.	Lowest Single Test.	Average Highest 10 Per cent of Tests.	Average Lowest 10 Per cent of Tests.	Average of all Tests.	Proportion of Tests within 10 Per cent of Average.	Proportion of Tests within 25 Per cent of Average.
	Reduced to 15 Per cent Moisture.							Per cent.	Per cent.
1	Longleaf pine	1,160	17,800	3,300	14,200	8,800	10,900	41	84
2	Cuban pine	390	17,000	2,900	14,600	8,800	11,900	46	83
3	Shortleaf pine	330	15,300	5,000	12,400	7,000	9,200	40	79
4	Loblolly pine	650	14,800	3,900	13,100	8,100	10,100	44	84
	Reduced to 12 Per cent Moisture.								
5	White pine	120	11,100	4,600	10,100	5,000	7,900	43	81
6	Red pine	95	12,900	3,100	12,300	4,900	9,100	28	60
7	Spruce pine	170	16,300	3,100	13,600	5,800	10,000	43	81
8	Bald cypress	655	14,800	2,300	11,700	5,000	7,900	25	69
9	White cedar	87	9,100	3,500	8,400	4,000	6,300	32	78
10	Douglas spruce*	41	13,000	3,800	12,000	4,100	7,900	22	58
11	White oak	218	20,300	5,700	18,500	7,600	13,100	39	75
12	Overcup oak	216	19,600	4,900	14,900	6,300	11,300	47	81
13	Post oak	49	16,400	5,100	15,300	7,400	12,300	47	92
14	Cow oak	256	23,000	3,300	12,500	6,500	11,500	32	68
15	Red oak	57	16,500	5,700	15,400	9,100	11,400	46	84
16	Texan oak	117	19,500	8,200	16,900	10,000	13,100	64	86
17	Yellow oak	40	15,000	5,100	14,600	5,700	10,800	28	65
18	Water oak	31	16,000	5,800	15,700	7,200	12,400	40	76
19	Willow oak	153	16,000	3,200	13,800	5,400	10,400	33	70
20	Spanish oak	257	17,300	5,000	15,600	6,900	12,000	40	72
21	Shagbark hickory	187	23,300	5,700	20,300	9,400	16,000	46	84
22	Mockernut hickory	75	20,700	5,300	19,700	7,900	15,200	45	78
23	Water hickory	14	18,000	5,300	17,300	5,400	12,500	21	64
24	Bitternut hickory	25	19,500	7,000	19,300	8,700	15,000	28	60
25	Nutmeg hickory	72	16,600	6,700	15,600	8,100	12,500	40	88
26	Pecan hickory	37	18,300	5,600	18,100	10,300	15,300	38	95
27	Pignut hickory	30	25,000	11,100	24,300	11,500	18,700	43	77
28	White elm	18	14,000	7,300	13,600	7,300	10,300	44	72
29	Cedar elm	44	19,200	6,600	17,300	8,500	13,500	50	86
30	White ash	87	15,000	5,000	14,200	6,300	10,800	37	77
31	Green ash	10	16,000	5,100	16,000	5,100	11,600	20	60
32	Sweet gum	118	14,400	5,100	12,700	6,000	9,500	39	79

* Actual tests on "dry" material not reduced for moisture.

TABLE XXXVII. — *Continued* — RESULTS OF TESTS IN BENDING — AT RELATIVE ELASTIC LIMIT

SUMMARY OF MECHANICAL TESTS ON THIRTY-TWO SPECIES OF AMERICAN WOODS

(Division of Forestry, Circular 15)

[Pounds per square inch]

No.	Species.	Number of Tests.	Highest Single Test.	Lowest Single Test.	Average of Highest 10 Per cent of Tests.	Average of Lowest 10 Per cent of Tests.	Average of all Tests.	Proportion of Tests within 10 Per cent of Average.	Proportion of Tests within 25 Per cent of Average.	Modulus of Elasticity (Average of all Tests).
	Reduced to 15 Per cent Moisture.							Per cent.	Per cent.	
1	Longleaf pine	1,160	13.500	2,400	11,100	5,400	8,500	43	81	1,890,000
2	Cuban pine	390	12,900	2,200	11,500	5,600	9,500	42	83	2,300,000
3	Shortleaf pine	330	11,900	2,900	9,700	4,800	7,200	48	81	1,600,000
4	Loblolly pine	650	12,700	3,100	10,800	5,400	8,200	46	85	1,950,000
	Reduced to 12 Per cent Moisture.									
5	White pine	130	10,000	4,100	8,200	4,500	6,400	58	85	1,390,000
6	Red pine	95	11,300	3,100	10,300	4,500	7,700	38	73	1,620,000
7	Spruce pine	170	13,700	3,000	11,200	5,000	8,400	51	82	1,640,000
8	Bald cypress	655	12,000	2,200	9,900	4,200	6,600	25	66	1,290,000
9	White cedar	87	8,200	3,400	7,390	4,000	5,800	44	86	910,000
10	Douglas spruce *	41	13,700	2,800	9,600	3,400	6,400	32	56	1,680,000
11	White oak	218	15,700	4,400	14,100	6,100	9,600	37	73	2,090,000
12	Overcup oak	216	11,600	4,000	9,500	5,400	7,500	47	91	1,620,000
13	Post oak	49	10,600	5,100	9,600	6,000	8,400	34	76	2,030,000
14	Cow oak	256	14,200	3,400	11,600	5,000	7,600	50	95	1,610,000
15	Red oak	57	14,500	5,100	13,600	5,600	9,200	15	49	1,970,000
16	Texan oak	117	12,000	5,900	11,400	7,800	9,400	62	94	1,860,000
17	Yellow oak	40	11,800	4,900	11,100	5,100	8,100	35	75	1,740,000
18	Water oak	31	11,800	4,500	11,400	5,500	8,800	40	84	2,000,000
19	Willow oak	153	13,100	2,700	10,000	4,300	7,400	42	81	1,750,000
20	Spanish oak	257	13,500	5,100	11,600	6,600	8,600	41	80	1,930,000
21	Shagbark hickory	187	16,100	5,400	14,200	7,700	11,200	50	89	2,390,000
22	Mockernut hickory	75	15,400	4,300	14,600	7,800	11,700	39	83	2,320,000
23	Water hickory	14	11,900	4,100	11,800	4,800	9,800	21	86	2,080,000
24	Bitternut hickory	25	14,300	7,500	14,000	7,600	11,100	44	84	2,280,000
25	Nutmeg hickory	72	12,200	4,200	11,200	6,400	9,300	46	93	1,940,000
26	Pecan hickory	37	15.000	5,800	14,400	7,900	11,500	65	89	2,530,000
27	Pignut hickory	30	17,500	7,400	16,400	8,300	12,600	40	83	2,730,000
28	White elm	18	9,700	5,300	9,600	5,400	7,300	33	71	1,540,000
29	Cedar elm	44	10,700	4,700	10,100	5,800	8,000	57	91	1,700,000
30	White ash	87	11,500	3,600	10,400	5,200	7,900	43.	88	1,640,000
31	Green ash	10	13,200	3,200	13,200	3,200	8,900	40	70	2,050,000
32	Sweet gum	118	11,000	3,500	10,100	5.100	7,800	46	82	1,700,000

* Actual tests on "dry" material not reduced for moisture.

TABLE XXXVII. — *Concluded* — RESULTS OF TESTS IN COMPRESSION, ACROSS GRAIN,* AND SHEARING WITH GRAIN

SUMMARY OF MECHANICAL TESTS ON THIRTY-TWO SPECIES OF AMERICAN WOODS

(Division of Forestry, Circular 15)

[Pounds per square inch]

No.	Species.	Number of Tests.	Compression across Grain.	Shearing with Grain not Reduced for Moisture.
	Reduced to 15 Per cent Moisture.			
1	Longleaf pine	1,210	1,000	700
2	Cuban pine	400	1,000	700
3	Shortleaf pine	330	900	700
4	Loblolly pine	690	1,000	700
	Reduced to 12 Per cent Moisture.			
5	White pine	130	700	400
6	Red pine	100	1,000	500
7	Spruce pine	175	1,200	800
8	Bald cypress	650	800	500
9	White cedar	87	700	400
10	Douglas spruce†	41	800	500
11	White oak	218	2,200	1,000
12	Overcup oak	216	1,900	1,000
13	Post oak	49	3,000	1,100
14	Cow oak	256	1,900	900
	Reduced to 12 Per cent Moisture. — *Concluded.*			
15	Red oak	57	2,300	1,100
16	Southern red oak	117	2,000	900
17	Black oak	40	1,800	1,100
18	Water oak	30	2,000	1,100
19	Willow oak	153	1,600	900
20	Spanish oak	255	1,800	900
21	Shagbark hickory	135	2,700	1,100
22	White hickory	75	3,100	1,100
23	Water hickory	14	2,400	1,000
24	Bitternut hickory	25	2,200	1,000
25	Nutmeg hickory	72	2,700	1,100
26	Pecan hickory	37	2,800	1,200
27	Pignut hickory	30	3,200	1,200
28	White elm	18	1,200	800
29	Cedar elm	44	2,100	1,300
30	White ash	87	1,900	1,100
31	Green ash	10	1,700	1,000
32	Sweet gum	118	1,400	800

* To an indentation of 3 per cent of the height of the specimen. † Actual tests on "dry" material not reduced for moisture.

TABLE XXXVIII. — STRENGTH VALUES FOR STRUCTURAL TIMBERS

(Forest Service, Circular 189)

BENDING TESTS ON GREEN MATERIAL

Species.	Sizes.		Number of Tests.	Per cent of Moisture.	Rings per Inch.	F. S. at E. L.		M. of R.		M. of E.		Calculated Shear.	
	Cross Section.	Span.				Average per Square Inch.	Ratio to 2" by 2".	Average per Square Inch.	Ratio to 2" by 2".	Average per Square Inch.	Ratio to 2" by 2".	Average per Square Inch.	Ratio to 2" by 2".
	Ins.	Ins.				Lbs.		Lbs.		1000 Lbs.		Lbs.	
Longleaf pine	12×12	138	4	28.6	9.7	4099	0.83	6710	0.74	1523	0.99	261	0.86
	10×16	168	4	26.8	16.7	4193	.85	6453	.71	1626	1.05	306	1.01
	8×16	156	7	28.4	14.6	3147	.64	5439	.60	1368	.89	390	1.29
	6×16	132	1	40.3	21.8	4120	.83	6460	.71	1190	.77	378	1.25
	6×10	180	1	31.0	6.2	3580	.72	6500	.72	1412	.92	175	.58
	6× 8	180	2	27.0	8.2	3735	.75	5745	.63	1282	.83	121	.40
	2× 2	30	15	33.9	14.1	4950	1.00	9070	1.00	1540	1.00	303	1.00
Douglas fir	8×16	180	191	31.5	11.0	3968	.76	5983	.72	1517	.95	269	.81
	5× 8	180	84	30.1	10.8	3693	.71	5178	.63	1533	.96	172	.52
	2×12	180	27	35.7	20.3	3721	.71	5276	.64	1642	1.03	256	.77
	2×10	180	26	32.9	21.6	3160	.60	4699	.57	1593	1.00	189	.57
	2× 8	180	29	33.6	17.6	3593	.69	5352	.65	1607	1.01	171	.51
	2× 2	24	568	30.4	11.6	5227	1.00	8280	1.00	1597	1.00	333	1.00
Douglas fir (fire-killed)	8×16	180	30	36.8	10.9	3503	.80	4994	.64	1531	.94	330	1.19
	2×12	180	32	34.2	17.7	3489	.80	5085	.66	1624	.99	247	.89
	2×10	180	32	38.9	18.1	3851	.88	5359	.69	1716	1.05	216	.78
	2× 8	180	31	37.0	15.7	3403	.78	5305	.68	1676	1.02	169	.61
	2× 2	30	290	33.2	17.2	4360	1.00	7752	1.00	1636	1.00	277	1.00
Shortleaf pine	8×16	180	12	39.5	12.1	3185	.73	5407	.70	1438	1.03	362	1.40
	8×14	180	12	45.8	12.7	3234	.74	5781	.75	1494	1.07	338	1.31
	8×12	180	24	52.2	11.8	3265	.75	5503	.71	1480	1.06	277	1.07
	5× 8	180	24	47.8	11.5	3519	.81	5732	.74	1485	1.06	185	.72
	2× 2	30	254	51.7	13.6	4350	1.00	7710	1.00	1395	1.00	258	1.00
Western larch	8×16	180	32	51.0	25.3	3276	.77	4632	.64	1272	.97	298	1.11
	8×12	180	30	50.3	23.2	3376	.79	5286	.73	1331	1.02	254	.94
	5× 8	180	14	56.0	25.6	3528	.83	5331	.74	1432	1.09	169	.63
	2× 2	28	189	46.2	26.2	4274	1.00	7251	1.00	1310	1.00	269	1.00
Loblolly pine	8×16	180	17	45.8	6.1	3094	.75	5394	.69	1406	.98	383	1.44
	5×12	180	94	60.9	5.9	3030	.74	5028	.64	1383	.96	221	.83
	2× 2	30	44	70.9	5.4	4100	1.00	7870	1.00	1440	1.00	265	1.00
Tamarack	6×12	162	15	57.6	16.6	2914	.75	4500	.66	1202	1.05	255	1.11
	4×10	162	15	43.5	11.4	2712	.70	4611	.68	1238	1.08	209	.91
	2× 2	30	82	38.8	14.0	3875	1.00	6820	1.00	1141	1.00	229	1.00
Western hemlock	8×16	180	39	42.5	15.6	3516	.80	5296	.73	1445	1.01	261	.92
	2× 2	28	52	51.8	12.1	4406	1.00	7294	1.00	1428	1.00	284	1.00
Redwood	8×16	180	14	86.5	19.9	3734	.79	4492	.64	1016	.96	300	1.21
	6×12	180	14	87.3	17.8	3787	.80	4451	.64	1068	1.00	224	.90
	7× 9	180	14	79.8	16.7	4412	.93	5279	.76	1324	1.25	199	.80
	3×14	180	13	86.1	23.7	3506	.74	4364	.62	947	.89	255	1.03
	2×12	180	12	70.9	18.6	3100	.65	3753	.54	1052	.99	187	.75
	2×10	180	13	55.8	20.0	3285	.69	4079	.58	1107	1.04	169	.68
	2× 8	180	13	63.8	21.5	2989	.63	4063	.58	1141	1.08	134	.54
	2× 2	28	157	75.5	19.1	4750	1.00	6980	1.00	1061	1.00	248	1.00
Norway pine	6×12	162	15	50.3	12.5	2305	.82	3572	.69	987	1.03	201	1.17
	4×12	162	18	47.9	14.7	2648	.94	4107	.79	1255	1.31	238	1.38
	4×10	162	16	45.7	13.3	2674	.95	4205	.81	1306	1.36	198	1.15
	2× 2	30	133	32.3	11.4	2808	1.00	5173	1.00	960	1.00	172	1.00
Red spruce	2×10	144	14	32.5	21.9	2394	.66	3566	.60	1180	1.02	181	.80
	2× 2	26	60	37.3	21.3	3627	1.00	5900	1.00	1157	1.00	227	1.00
White spruce	2×10	144	16	40.7	9.3	2239	.72	3288	.63	1081	1.08	166	.83
	2× 2	26	83	58.3	10.2	3090	1.00	5185	1.00	998	1.00	199	1.00

TABLE XXXVIII.—*Continued*

COMPRESSION AND SHEAR TESTS ON GREEN MATERIAL

TABLE XXXIX. — UNIT STRESSES FOR STRUCTURAL TIMBER RECOMMENDED BY THE COMMITTEE ON WOODEN BRIDGES AND TRESTLES

AM. RY. ENG. ASSN.

[Pounds per Square Inch]

Kind of Timber.	Bending.			Shearing.				Compression.						Ratio of Length of Stringer to Depth.
	Extreme Fiber Stress.		Modulus of Elasticity.	Parallel to Grain.		Longitudinal Shear in Beams.		Perpendicular to Grain.		Parallel to Grain.		For Columns under 15 Diams. Safe Stress.	Formulas for Safe Stress in Long Columns over 15 Diams.	
	Average Ultimate.	Safe Stress.	Average.	Average Ultimate.	Safe Stress.	Average Ultimate.	Safe Stress.	Elastic Limit.	Safe Stress.	Average Ultimate.	Safe Stress.			
Douglas fir	6100	1200	1,510,000	690	170	270	110	630	310	3600	1200	900	$1200\left(1-\frac{L}{60D}\right)$	10
Longleaf pine...	6500	1300	1,610,000	720	180	300	120	520	260	3800	1300	980	$1300\left(1-\frac{L}{60D}\right)$	10
Shortleaf pine...	5600	1100	1,480,000	710	170	330	130	340	170	3400	1100	830	$1100\left(1-\frac{L}{60D}\right)$	10
White pine......	4400	900	1,130,000	400	100	180	70	290	150	3000	1000	750	$1000\left(1-\frac{L}{60D}\right)$	10
Spruce..........	4000	1000	1,310,000	600	150	170	70	370	180	3200	1100	830	$1100\left(1-\frac{L}{60D}\right)$	......
Norway pine...	4200	800	1,190,000	590	130	250	100	......	150	2600*	800	600	$800\left(1-\frac{L}{60D}\right)$	......
Tamarack......	4600	900	1,220,000	670	170	260	100	......	220	3200*	1000	750	$1000\left(1-\frac{L}{60D}\right)$	......
Western hemlock..........	5800	1100	1,480,000	630	160	270*	100	440	220	3500	1200	900	$1200\left(1-\frac{L}{60D}\right)$	......
Redwood.......	5000	900	800,000	300	80	......	.....	400	150	3300	900	680	$900\left(1-\frac{L}{60D}\right)$	......
Bald cypress....	4800	900	1,150,000	500	120	......	......	340	170	3900	1100	830	$1100\left(1-\frac{L}{60D}\right)$	......
Red cedar......	4200	800	860,000	......	......	......	......	470	230	2800	900	680	$900\left(1-\frac{L}{60D}\right)$	......
White oak......	5700	1100	1,150,000	840	210	270	110	920	450	3500	1300	980	$1300\left(1-\frac{L}{60D}\right)$	12

* Partially air-dry. D = least side in inches; L = length in inches.

Note. — These unit stresses are for a green condition of timber and are to be used without increasing the live-load stresses for impact.

The difference between green and seasoned wood may amount to as much as 50 per cent as shown by Table XL. The influence of seasoning consists in (1) bringing by means of shrinkage about 10 per cent more fibers into the same square inch of cross section than are contained in the wet wood; (2) shrinking the cell-wall itself by about 50 per cent of its cross section and thus hardening it, just as a cowskin becomes thinner and hardens by drying.

Table XL applies only to small, clear pieces of wood seasoned under special conditions with great care. The Forest Service has found * that a comparison of the results of tests on seasoned material with those from tests on green material shows that, without exception, the strength of 2 by 2 inch specimens is increased by lowering the moisture content, but that increase in strength of other sizes is

* Strength Values for Structural Timbers. McGarvey Cline. Forest Service, Circular 189, Jan. 25, 1912.

much more erratic. Some specimens, in fact, show an apparent loss in strength due to seasoning. In the light of these facts it is not safe to base working stresses on results secured from any but green material.

TABLE XL.—REDUCTION FACTORS FOR STRESS AT ELASTIC LIMIT IN BENDING OF LONGLEAF PINE

(Forest Service, Bulletin 70)

To — Moisture per cent.	From — Moisture per cent. 2	4.	6.	8.	10.	12.	14.	16.	18.	20.	22.	24.	26.*
2	1	1.13	1.31	1.53	1.75	1.99	2.20	2.39	2.54	2.70	2.85	2.99	3.14
4	.882	1	1.15	1.35	1.54	1.75	1.94	2.11	2.25	2.39	2.52	2.64	2.77
6	.767	.867	1	1.17	1.34	1.52	1.69	1.83	1.95	2.07	2.18	2.29	2.41
8	.656	.742	.856	1	1.15	1.30	1.44	1.57	1.67	1.77	1.87	1.96	2.06
10	.572	.648	.746	.882	1	1.13	1.26	1.37	1.45	1.54	1.63	1.71	1.80
12	.503	.570	.657	.768	.881	1	1.11	1.20	1.28	1.36	1.44	1.51	1.58
14	.455	.515	.594	.694	.795	.904	1	1.09	1.16	1.23	1.30	1.36	1.43
16	.419	.475	.547	.639	.733	.832	.921	1	1.07	1.13	1.19	1.25	1.32
18	.393	.445	.513	.600	.688	.781	.865	.938	1	1.06	1.12	1.17	1.24
20	.370	.420	.485	.565	.648	.735	.814	.884	.941	1	1.05	1.11	1.16
22	.351	.397	.458	.535	.614	.697	.771	.838	.893	.948	1	1.05	1.10
24	.335	.379	.437	.510	.585	.665	.735	.799	.851	.904	.954	1	1.05
*26	.318	.361	.415	.486	.556	.633	.700	.760	.810	.860	.908	.951	1

* Green.

A recent instructive series of tests* have been conducted by W. K. Hatt in the Laboratory for Testing Materials of Purdue University, in coöperation with the Wood Preservation Committee of the American Railway Engineering Association and with the following organizations:

Big Four Railroad Company.
Illinois Central Railroad Company.
American Creosoting Company.
Ayer and Lord Tie Company.
Atchison, Topeka and Santa Fe Railway Company.
Forest Service, U. S. Department of Agriculture.

The principal results of these tests are shown in Table XLI. One of the main determinations of the tests was of the resistance of the ties to the direct pressure of the rail. It was shown that the various treatments had not weakened the ties, except in the case of ties newly treated with crude oil.

The tie was put through a planer, so that one surface was true. The other surface was adzed at the place of bearing to provide a true bearing for the plate representing the bottom of the rail or the tie plate.

* Fourth Progress Report of Tests on Treated Ties, Proceedings Am. Ry. Eng. & M. of W. Assn., 1910, Vol. 11, Part 2.

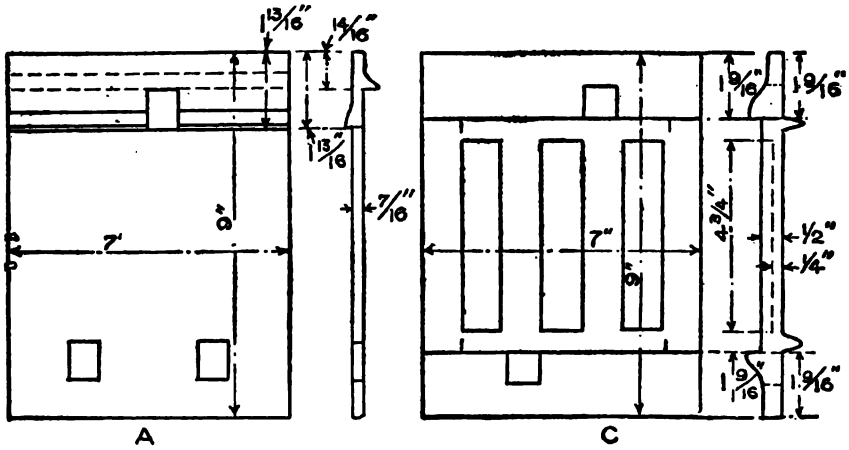
TABLE XLI. — BEARING STRENGTH OF TIES UNDER THE RAIL

(See Proceedings Am. Ry. Eng. & M. of W. Assn., Vol. 11, Part 2, pp. 853-4)

	Natural.		Treated.		Remarks.
	No. of Tests.	Crushing at E. L.	No. of Tests.	Crushing at E. L.	
		Lbs. per sq. in.		Lbs. per sq. in.	
Red oak	100	1090	100	1080	
Loblolly pine	70	612	70	591	1. Crude oil, 529.
Shortleaf pine	30	640	30	618	1. Crude oil, 373.
Longleaf pine	20	688	20	725	
Red gum	29	830	29	791	1. Crude oil, 655.
Total	249		249		

Tests were made upon 581 half-ties to determine the relation of the crushing strength of the ties with and without the tie plates.

The fiber stress per unit of area of wood under the tie plate at the elastic limit in the case of the oak are less than those under the rail alone except for plate C (see Fig. 124). Of course, the total load is greater. This is accounted for by the perceptible springing of the tie plates, thus producing a non-uniform pres-



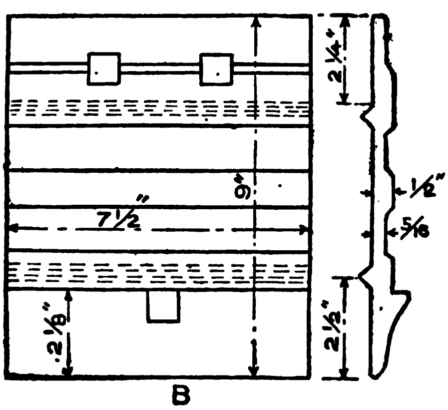


Fig. 124.—Tie Plate Forms used in Tests at Purdue University.

Fiber Stress in Tie Plates at Elastic Limit: A 37,500 lbs. per sq. in.; B 68,800 lbs. per sq. in.; C 59,800 lbs. per sq. in.

sure on the wood under the tie plate. The loads, therefore, carried with the aid of a tie plate, while larger, are not increased in the same ratio as the increase of bearing surface.

In the loblolly-pine ties and in plate C on red oak, no perceptible springing of the tie plate was observed within the elastic limit of the timber, the load being increased in practically the same ratio as the surface.

Tie plate A (see Fig. 124), $\frac{7}{16}$ inch thick, was permanently bent at the edge of the rail bearing when the test was carried to $\frac{1}{4}$-inch compression on oak ties. The yielding was confined almost entirely to the edge of the rail bearing.

Tie plate B, $\frac{1}{2}$ inch thick at edge of the rail, was not permanently bent by the same test. It, however, springs as much, or more, than plate A, but the springing was more uniform. Plate B is harder metal, and this would seem to be an advantage in this test.

The three tie plates were tested under flexure to determine the quality of the metal. The results are shown in Fig. 124.

In the calculations of the strength of the tie, if we take the strength of the wood as shown by Table XLII, the result will be not far from correct. The working stress at the rail bearing given in the table refers to the allowable stress under the tie plate.

TABLE XLII

WORKING STRESSES FOR TIE TIMBER

Kind of Wood.	Working Stress (Pounds per Square Inch).	
	Compression at Rail Bearing.	Extreme Fiber Stress in Cross Bending.
Oak	500	1000
Longleaf pine	325	1200
Inferior woods	200–250	750

Examining the safe load the tie in the track will carry, we have to consider two sources of possible failure of the tie:

1. The compression of the fibers under the tie plate.
2. The rupture of the tie due to too great a bending moment in the tie.

A 6 by 9-inch tie plate gives an area of 54 square inches. Referring to Table XLII, we find the permissible load on the tie plate to be 27,000 pounds for oak ties, 17,500 pounds for longleaf yellow pine, and about 11,000 to 13,000 pounds for the inferior woods.

Let us now consider the bending moment in the tie.

If the tie were completely rigid, there would result a uniform distribution of the pressure on the ballast. This is, however, never realized, and there is an unequal distribution of the pressure.

The tie should be considered as a continuous beam, supporting a vertical load at two points and resting on material which is, within certain limits, compressible. Exactly what takes place in the ballast under the loaded tie is of the greatest importance in determining the bending of the tie.

* M. Coüard found that the vertical displacements of cross-ties hardly reach three millimeters ($\frac{1}{8}$ inch), and that they are not proportional to the weights supported. He has concluded from his experiments that "the cross-ties fixed to the rail remain, at certain points, suspended above the ballast, and that right at the rail there is formed under even the best tamped cross-ties some depressions of ballast on the edges of which the cross-tie is supported; that under the passage of a wheel even lightly loaded the cross-ties come in contact with the ballast and deflect to the depth of the depressions."

Shwedler, Hoffman, Schwald, Riese, and Zimmerman, from the theoretical researches of Winckler, have derived the elastic curve of the tie represented

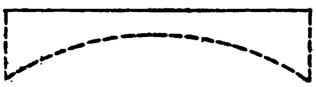


FIG. 125. — Elastic Curve of Tie, 7 feet 10.4 inches long. (After Winckler.)

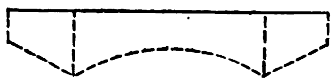


FIG. 126. — Elastic Curve of Tie, 8 feet 10.3 inches long. (After Winckler.)

by Fig. 125 or Fig. 126, according as the cross-tie was 2 m. 40 (7 feet 10.4 inches) or 2 m. 70 (8 feet 10.3 inches) long.

Very careful experiments have been made by M. Cuënot on the relative action of the tie and the ballast.† The following record of his tests is taken from Mr. W. C. Cushing's translation of his work:

"The rails employed were of the type used on the Paris, Lyons and Mediterranean, either the P. M. type, of a weight of 39 kilograms per running meter (78.6 pounds per yard), or the P. L. M.-A. type, of a weight of 34½ kilograms per running meter (69.5 pounds per yard).

"All my experiments, during nearly three years, have been made, first, on a side track, then on track No. 2 of the line from Mouchard to Bourg, traversed by the express and fast trains, comparatively with oak cross-ties employed on the P. L. M. system, and with composite cross-ties (wood and steel). (See Fig. 127.) Finally, a special track for experiments was laid at the Bourg

* Revue des Chemins de Fer, July, 1897.

† Deformations of Railroad Tracks and the Means of Remedying Them. G. Cuënot, 1907, New York.

station, and there was tested, at the same time as the two types of cross-ties mentioned, the metallic cross-tie in use on the State System.

"The wooden cross-ties were oak, creosoted, and of the following dimensions:

Length..................	2 m. 60	(8 ft. 6.36 in.)
Width...................	0 m. 22 to 0 m. 25	(8.66 in. to 9.84 in.)
Depth...................	0 m. 14 to 0 m. 15	(5.51 in. to 5.91 in.)

"The composite cross-tie was composed of a metallic skeleton in the form of an inverted trough, provided in the interior with two symmetrical blocks of wood solidly fixed, and leaving between them an empty central space."

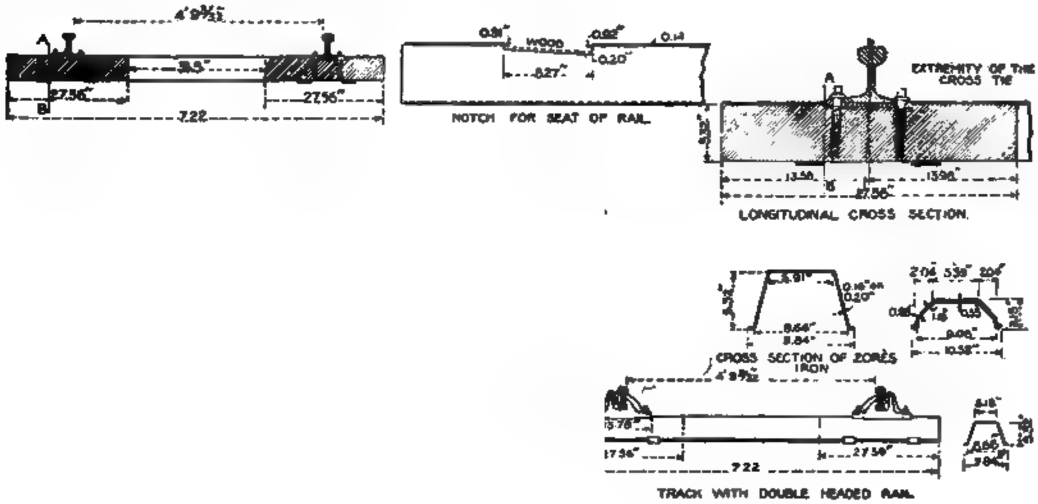


FIG. 127. — Wood and Composite Ties used in Cuënot's Experiments.

The measuring apparatus for experiments in the static state was as follows:

"There were first placed in the surface of the wood cross-ties, screws with square heads distributed over their whole length and giving 15 or 16 fixed points, which were to serve as bench marks for the determination of the deformation. A rigid steel rule in the form of a T (Fig. 128) presented, right at the points, whose spacing was the same for all cross-ties, vertical rods terminated by a notch, in which was brought, while resting on the screw with square head, a gage in the form of an inclined plane, whose divisions were calculated in a manner to correspond with a tenth of a millimeter. The inclination of the inclined plane had been so chosen that the interval between two divisions was at least of 2 centimeters ($\frac{79}{100}$ inch), which allowed estimating the tenth of a millimeter with exactness.

"The rule was fixed in an unchangeable manner to two stakes of strong dimensions, buried in the embankment about 1 m. 10 (3.61 feet), in order to eliminate the influence of the load on the supports of the rule. When the rule was in place, an observer introduced the wedge-shaped gage in the notch, while maintaining it horizontally on the head of the screw, and stopped it at the moment when it commenced to become wedged; he then made a first read-

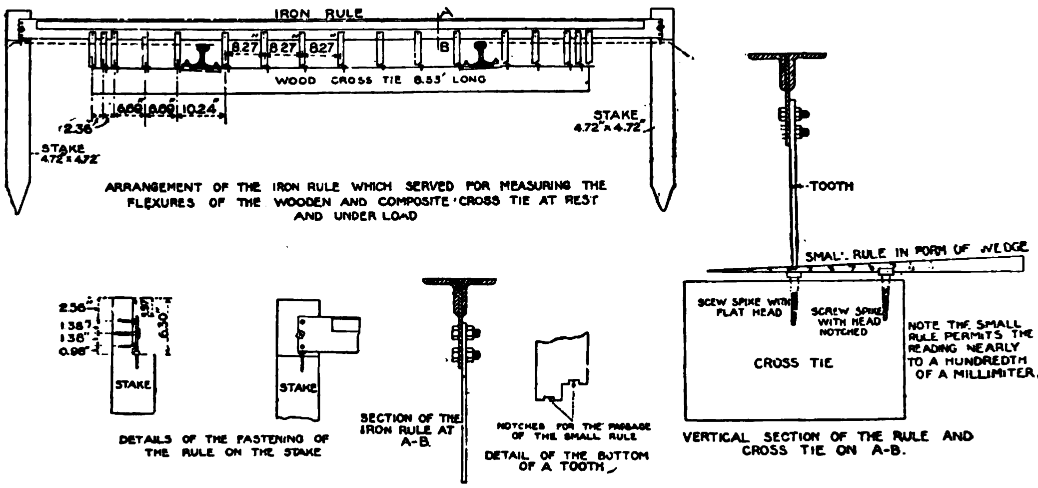


Fig. 128. — Measuring Apparatus for Ties under Static Load. (Cuënot.)

ing on all the points of reference, proceeding, for example, from left to right, then a second, proceeding in the reverse direction, from right to left. The readings made were recorded and the mean taken, which thus gave the actual position of the cross-tie.

"The vehicle, which served to load the cross-tie considered, was brought up, always taking care to place the same wheels at the same spot with reference to the piece submitted to the test; it was allowed to remain during about 10 minutes, and the readings were recommenced. Two successive readings were made, and the mean of them was taken. The difference between the inscribed means gave the deformation of a cross-tie under the load considered.

"The measuring apparatus (see Fig. 129) for the experiments in the dynamic state was essentially composed of a stylus arranged in a stable manner at the face of a plate of smoked glass and fixed on the points of the cross-tie under observation. The black smoke deposited on the glass plate, which was displaced at the same time and by the same amount as the points, was removed by the point of the stylus; the height of the part removed gave the value of the deflection, or of the raising, of a cross-tie at the points considered. The

reading of this height was made by means of a magnifying glass nearly to the tenth of a millimeter.

"The stylus, with a flat point of tempered steel, was mounted on a very flexible spring, which could be approached to or removed from the glass plate at will, with the aid of a thumbscrew. The glass plate was fixed by screws on one of the faces of a cross-tie, then smoked in a flame of a candle at the moment when it was desired to put it in service. The thumbscrew passed through an iron rod and simply rested on the spring, which, left free, moved back and forth on the rod fixed by means of two bolts on a stake deeply buried in the soil.

"In order to make an observation, the screw is pressed against the spring until the point of the stylus comes in contact with the blackened plate. In this position a light blow is given to it, which makes it oscillate and defines a horizontal trace of 2 or 3 millimeters' ($\frac{8}{100}$ to $\frac{12}{100}$ inch) length on the black smoke, which forms the reference mark.

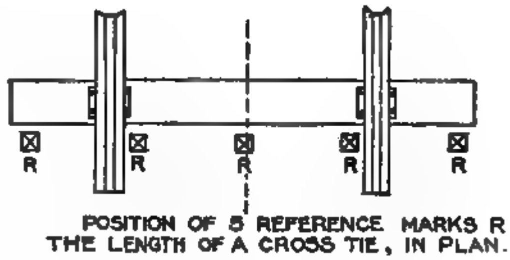


Fig. 129. — Measuring Apparatus for Ties under Dynamic Load. (Cuënot.)

"At this moment one can either place the vehicle on the cross-tie, or allow trains at speed to pass over it. The height of the part of the glass plate rubbed off by the point of the stylus gives, above the reference mark, the values of the depression, and below, the uplift, of the cross-tie. The latter is always inferior to the former; for the flexure is important in comparison with the movement of uplift of this piece under the influence of loads at a distance. The successive influence of each of the axles cannot be noted, but it is solely a maximum indication which is produced."

The results of the dynamic tests were always slightly less than those obtained from the static tests. Fig. 130 shows the general results from the large number of experiments made.

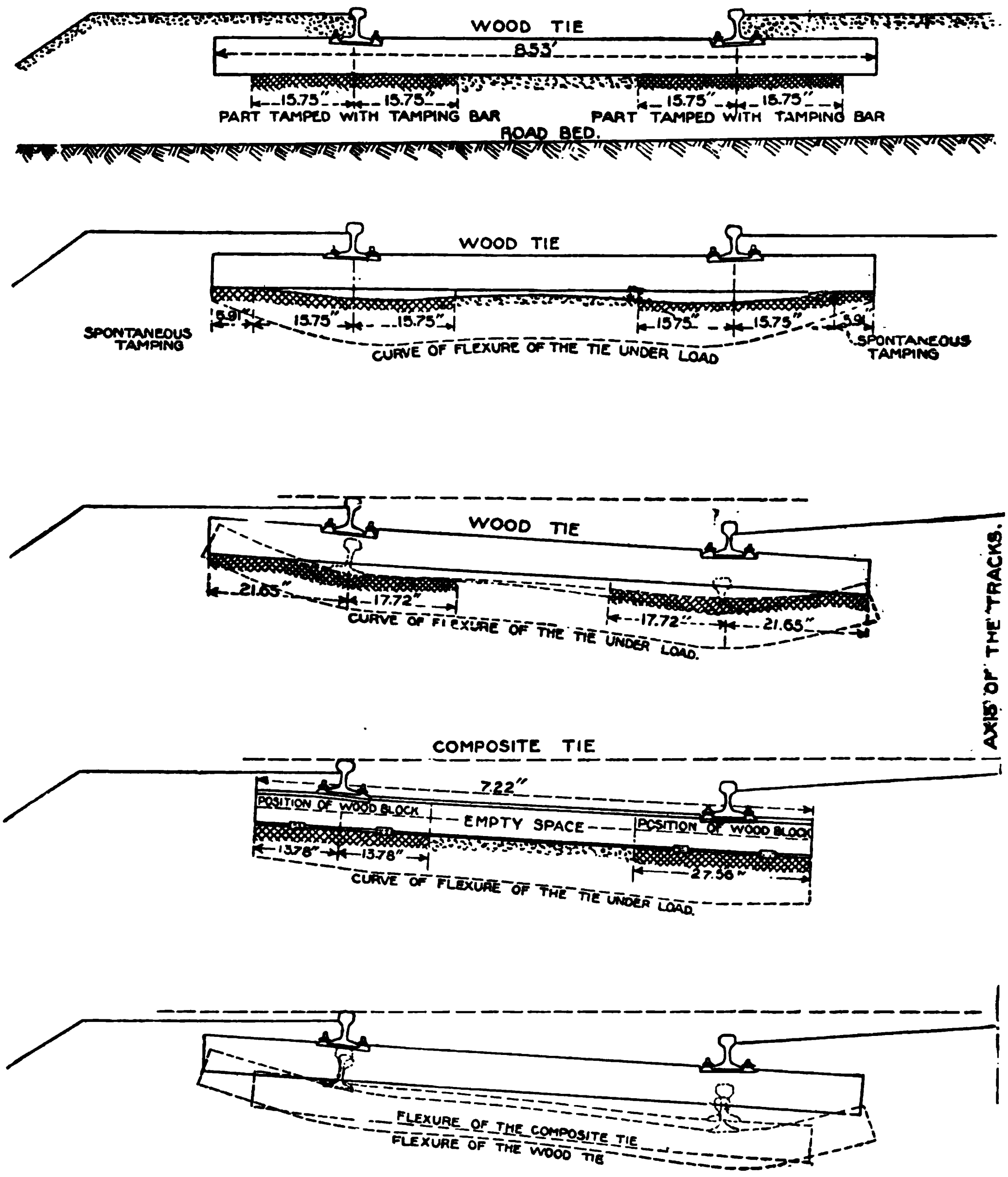


Fig. 130. — Results of M. Cuënot's Tests on Ties.

The following conclusions have been drawn by M. Cuënot from his experiments:

"(*a*) The long ties, 8 feet 6.36 inches to 7 feet 6.6 inches, take, under the load, the form of a basin with the bottom slightly raised in the center.

"(*b*) The short ties, 7 feet 0.6 inch to 6.5 feet, are deformed according to a curve, convex or otherwise, and inclined toward the extremity.

"(c) The ties between 7 feet 0.6 inch and 7 feet 2.64 inches are lowered parallel with themselves without sensible curvature.

"(d) The unsymmetrical tamping raised the curve towards the center; a very feeble lack of symmetry reacts very clearly in this direction.

"(e) It is possible, by increasing the rigidity of a cross-tie, notably by concentrating the material about the supports, to reduce its sinking to the quantity which is intended as a limit, and its flexure in such measure as one would wish.

"(f) The permanent sinking of the ballast is variable according to the case, but the elastic sinking, the only one there is reason to consider, is, so to speak, constant, whatever be the length and type of the cross-tie adopted. The deformation is slowly produced and augments with time."

It is here seen that a tie 8 feet 6 inches long, which is the usual length of tie employed in this country, under proper conditions of tamping, will assume

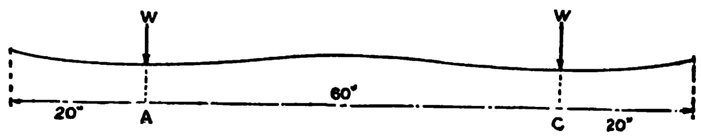


FIG. 131. — Strain Diagram of Entire Tie.

the loaded position shown in Fig. 131. In the figure, the loads W at A and C represent the load at each rail.

Considerations of the tamping under the tie will not admit of any exact mathematical formula for the distribution of the pressure of the ballast. If, however, as a working hypothesis, we assume that the pressure of the ballast is uniformly distributed between the rails and that the pressure is similarly uniformly distributed, but of greater intensity from the rail to the end of the tie, and, further, that the tangent to the elastic curve of the loaded tie is horizontal under the points of support of the rail, then approximate formulæ can be readily derived for the maximum bending moment in the tie and the greatest intensity of pressure of the ballast in terms of the load on the tie at either rail bearing.

This assumption, while not taking into account all the conditions of the loading of the ballast nor giving the exact distribution of pressure under the tie, will, nevertheless, when applied to an 8-foot 6-inch wood tie, afford a means of determining the maximum bending moment and the greatest intensity of pressure with sufficient accuracy for our purpose, and very possibly as exactly as the present state of our knowledge of the subject warrants.

Where it is desired to investigate the action of ties in a more thorough manner, the calculations may be proceeded with in the same manner as those for the case where the rail acts as a continuous girder in Article 23. It should be borne in mind, however, that the coefficient of the ballast or the ratio of pressure to sinking is not the same for all parts of the tie, but with proper conditions of tamping is considerably greater under the tie in the region adjacent to the rail bearing.

Referring to Fig. 132, the moments at the supports A and C are equal and each $\frac{1}{12}\ W'L'$, where W' is the total load uniformly distributed over

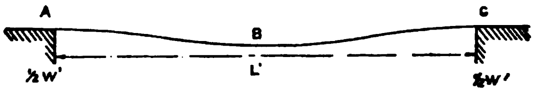


Fig. 132. — Strain Diagram of Tie between Rails.

the span L'. The bending moment at the center of the span B is $\frac{1}{24}\ W'L'$. Therefore, the maximum bending moment occurs at the supports and is $M_m = \frac{1}{12}\ W'L'$.

The free part of the tie outside the rail acts as a cantilever; the maximum bending moment occurs at C and is $M_c = \frac{1}{2}\ W''L''$, where W'' is the total load uniformly distributed over the span L'' (Fig. 133).

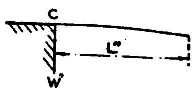


Fig. 133. — Strain Diagram of Tie outside of Rails.

Considering the tie as a whole, Fig. 131, we have, from the principle of the continuous girder, $M_c = \frac{1}{12}\ W'L' = \frac{1}{2}\ W''L''$, but for an effective length of the tie of 100 inches, $L' = 60$ inches and $L'' = 20$ inches;

therefore
$$\frac{1}{12}\ W'\ 60 = \frac{1}{2}\ W''\ 20$$
$$W' = 2\ W''.$$

But the reaction at any support is equal to the algebraic sum of the shear to the right and left of the support, and

$$W = J_{cl} + J_{cr}$$
$$W = \tfrac{1}{2}\ W' + W''$$
$$W = \tfrac{1}{2}\ W' + \tfrac{1}{2}\ W'$$
$$W = W' = 2\ W'',$$

where

W = the load at either rail bearing,

J_{cl} = the shear immediately to the left of C,

J_{cr} = the shear immediately to the right of C.

Substituting the value of W' in the equation for the maximum bending moment,

$$M_m = M_a = M_c,$$
$$M_m = \tfrac{1}{12} W \times 60,$$
$$M_m = 5\,W,$$

where

M_m = maximum bending moment,
M_a = bending moment at A,
M_c = " " " C.

The extreme fiber stress, $f = \dfrac{My}{I} = \dfrac{5\,Wy}{I}$, or $W = \dfrac{fI}{5\,y}$.

For a rectangular tie, $\dfrac{I}{y} = \dfrac{bh^3}{12} \div \dfrac{h}{2} = \dfrac{bh^2}{6}$,

and $W = \dfrac{fbh^2}{30}$.

Turning to Table XLII, we find the allowable extreme fiber stress in bending 1000 pounds per square inch for oak, and 750 pounds per square inch for the inferior woods. We can, therefore, prepare Table XLIII, showing the safe load that the tie can bear and not exceed a proper bending stress.

TABLE XLIII. — ALLOWABLE LOAD ON TIE AS DETERMINED FROM EXTREME FIBER STRESS IN BENDING

Kinds of Wood	Size of Tie.	Allowable Load Applied at Each Rail Bearing.
	Inches.	Pounds.
Oak	7×8	13,100
Oak	7×9	14,700
Oak	*Half round	15,000
Inferior woods	7×8	9,800
Inferior woods	7×9	11,000
Inferior woods	*Half round	11,300

* See Fig. 81.

17. Bearing on the Ballast

Considering now the bearing power of the ballast on which the tie rests, the maximum loading on the ballast under the tie per linear inch of the tie, from the preceding article, is

$$\frac{W''}{20} = \frac{W}{2 \times 20}.$$

To express W in terms of the bearing power per square foot of the ballast (p), and the width in inches of the base (b), we have the allowable load per linear inch of the tie equal to

$$\frac{bp}{144} = \frac{W}{2 \times 20},$$

or

$$W = \frac{bp}{3.6}.$$

For bearing on gravel or broken stone, not well confined, three tons per square foot is as much as should be allowed.

We may now prepare Table XLIV, showing the safe load that can be applied at each rail bearing as determined by the proper load on the ballast.

TABLE XLIV. — ALLOWABLE LOAD ON THE TIE AS DETERMINED BY THE SAFE LOADING OF THE BALLAST

Width of Base of Tie.	Allowable Pressure Applied at Each Rail Bearing of the Tie.
Inches.	Pounds.
8	13,500
9	15,000
*12	20,000

* See Fig. 81.

18. Bearing on the Subgrade

Before assuming a proper bearing under the tie, an examination must be made of the distribution of the load to the subgrade. The following experiments have been made in Germany to determine the distribution of force upon the subgrade.*

An experimental box, 37 inches long, 20 inches high, and 6 inches wide, was filled with a layer of clay 8 inches high at the bottom, on top of which was placed a layer of sand 6 inches high, and then a layer of gravel 6 inches high, upon which a tie was laid. This tie was tamped with the ordinary tamping pick and then subjected to a load of 57 pounds per square inch, or 8200 pounds per square foot, by which the rail level was depressed. By the use of an eccentric the loading was alternately lifted from the tie and again returned, thus imitating the process of passing a loaded wheel over the track. As soon as the tie had settled 1.2 inches, which was registered upon an attached sliding plate, the tie was again raised and tamped. From time to time photog aphic views and observations as to the stage or condition of the experiment were taken

* Glaser's Annalen für Gewerbe und Bauwesen. May, 1899. (Director Schubert.) Translation appears in Proceedings Am. Ry. Eng. & M. of W. Assn., Vol. 7, p. 105.

by removing the front wall of the experimental box. After the eleventh tamping the experiment was considered as completed, and the section shown in Fig. 134 was taken.

From this view we can easily see how a short depression, measuring about 12 inches to 14 inches wide, has been formed in the clay, with an upward swelling

FIG. 134. — Ballast Experiments — Schubert. Six inches of sand and 6 inches of gravel.

on each side. The pressure transmitted from the tie has accordingly distributed itself over this small width when the depth below the bottom of the tie was 12 inches.

In a subsequent experiment, broken stone was used in place of gravel; otherwise the procedure was the same. From a photograph of the section after the fifth tamping (see Fig. 135) a depression in the clay extending nearly

FIG. 135. — Ballast Experiments — Schubert. Six inches of sand and 6 inches of stone.

over the entire width of the experimental box (27½ inches to 29½ inches wide) is noticeable. The distribution of the force is consequently double that of the previous experiment.

Still more favorable appears this distribution when the height of the stone ballast is increased. In doing this, it is judicious to retain a thin layer of sand so as to prevent the larger pieces of broken stone from entering into the clay.

As will appear from the section shown in Fig. 136, a depression in the clay has not taken place, and only a few of the broken stones have gone through the sand to the clay. In emptying the box only a very unimportant depression was noticeable.

Fig. 136. — Ballast Experiments — Schubert. Stone with thin layer of sand.

Finally, the behavior of a foundation layer was investigated, and after the fourth tamping the section shown in Fig. 137 was taken. The stones of the foundation layer have penetrated the clay rather deep, and not only those in the center, but also stones on the sides, from which we can conclude that

Fig. 137. — Ballast Experiments — Schubert. Stone resting on clay subgrade.

the force transmitted through the tie has distributed itself nearly over the entire width of the box.

Hence, the most favorable distribution of forces is accomplished by the use of ballast of broken stone, with or without a foundation layer. The latter is, however, not suitable in a yielding subgrade, inasmuch as the stones penetrate into the grade, and the yielding soil will swell into the spaces, thus making the drainage ineffective.

The effect of overloading the subgrade is very clearly shown in Fig. 138.

* The road department of the Pennsylvania Railroad has installed an interesting piece of apparatus on the grounds of the South Altoona foundry to test the bearing qualities of different kinds of roadway and ballast. The

FIG. 138. — Effect of Overloading the Subgrade. (Am. Ry. Eng. Assn.)

particular ballast or subgrade to be tested is placed in three heavy boxes that extend across the track and have sufficient depth to serve the purpose. The track crosses this on a level and extends out on either side, terminating in a short

FIG. 139. — Pennsylvania Track Testing Apparatus. (Railway Age Gazette.)

and sharp incline. A four-wheel car on this track is loaded with pig metal to obtain any desired weight on the wheels. This car is also equipped with electric motors. A shed built across the track carries an overhead rail, from which a motor current is obtained, and a contact shoe is on the car. Fig. 139 illustrates the apparatus.

* Railway Age Gazette, June 11, 1909, and July 21, 1911.

When current is turned on, the car moves out to the end of the conductor rail, and here, as the contact is broken, the power of the motor is shut off. The car runs on until stopped by the adverse grade, and meanwhile a trip reverses the current connections to the motor. Stopped by the grade, the car runs back, beneath the current rail, when its motor drives it to the other end, where the movement is again reversed. In this way the car is made to travel back and forth automatically over the track until the desired results are obtained, the number of trips being automatically registered upon a counter.

These tests are the most extensive of the kind ever conducted in this country. It was felt that while the data obtained by Mr. Schubert were very instructive yet more valuable data could be obtained from a series of experiments if made in a manner more nearly approaching actual track conditions.*

The track was 109 feet in length, built of new P. R. R. standard 85-pound rail with 7-inch by 9-inch by 8½-foot ties spaced 25½ inches center to center. It being impracticable to run the car faster than about five miles per hour, at which speed any effect upon the track, due to impact alone, would be negligible, a weight of 75,000 pounds per axle was chosen for the experimental truck.

A series of five tests has been completed; the first one beginning on Sept. 2, 1908, and the last one ending on Aug. 2, 1910. Table XLV gives general data of the tests. Water was applied by sprinkling the boxes to observe the effect of moisture on the ballast; the amount applied in each test is shown in the table by inches of rainfall.

In test No. 1 the line of demarkation between the bottom of the ballast and the roadbed material was not straight. The test showed conclusively that a depth of 8 inches of trap-rock ballast, when laid on the usual roadbed material, was not sufficient to distribute the weight carried by the ties uniformly over the roadbed.

The results in the third box showed, however, that if 12 inches of permeable material, such as cinder, were used beneath the 8 inches of ballast, the distribution of the weight over the roadbed material was much better.

The results of the first test led to the second test to determine how a depth of 12 inches, 18 inches, and 24 inches of trap rock under the ties would behave. In test No. 2 the dividing line between the ballast and the loam was quite straight in box No. 3, but in boxes Nos. 1 and 2 there existed some depressions in the line especially under the rail.

* Experiments to Determine the Necessary Depth of Stone Ballast. Report of the General Manager's Committee Pennsylvania Railroad. Proceedings Am. Ry. Eng. Assn., 1912, Vol. 13.

A study of the sections in test No. 3 showed that the loam was more evenly depressed in box No. 3 than in the other boxes where stone had been substituted for part of the cinder during the test.

Test No. 4 showed that the gravel and slag distributed the pressure upon the loam with about the same efficiency.

Test No. 5 was made to determine whether a combination of rock and cinder would prove as satisfactory as the rock alone. It was found, however, that the line between the ballast and the loam in box No. 3 was not as good as in box No. 3 of Test No. 2.

TABLE XLV. — SUMMARY OF ROADBED TESTS AT ALTOONA.

Test No.	1	2	3		4		5	
			1st Part.	2nd Part.	1st Part.	2nd Part.	1st Part.	2nd Part.
From to	Sept. 2, 1908 Jan. 5, 1909.	Apr. 18, 1909 June 15, 1909.	June 28, 1909 July 20, 1909.	July 21, 1909 Aug. 6, 1909.	Oct. 19, 1909 Nov. 17, 1909.	Nov. 17, 1909 Dec. 3, 1909.	May 19, 1910 June 24, 1910.	June 24, 1910 Aug. 2, 1910.
Material in Box No. 1	8″ trap rock 27″ bad clay	12″ trap rock 26″ loam	24″ cinder 12″ loam	Removed 8″ cinder from top and replaced with trap rock	24″ slag 12″ sandy loam	8″ slag removed and 8″ trap rock added	24″ cinder 13″ sandy loam	6″ cinder removed and 6″ trap rock added
Box No. 2	8″ trap rock 27″ sandy loam	18″ trap rock 19″ loam	24″ cinder 12″ loam	Removed 12″ cinder from top and replaced with trap rock	24″ slag 12″ sandy loam	12″ slag removed and 12″ trap rock added	24″ cinder 13″ sandy loam	8″ cinder removed and 8″ trap rock added
Box No. 3	8″ trap rock 12″ cinder 15″ bad clay	24″ trap rock 14″ loam	24″ cinder 12″ loam	Unchanged	24″ sandy gravel 12″ sandy loam	12″ gravel removed and 12″ trap rock added	24″ cinder 13″ sandy loam	10″ cinder removed and 10″ trap rock added
No. of round trips	81,600	49,932	45,500	40,100	45,561	40,060	19,210	93,094
Settlement:								
Box No. 1	10 3/16″	8 1/4″	8 1/4″	2 3/4″	12 1/4″	4 1/4″	2 3/4″	5 1/4″
Box No. 2	14 1/16″	9 1/4″	8 1/2″	2 1/2″	13 1/4″	4 1/4″	2 1/2″	5 7/16″
Box No. 3	10 1/4″	9 1/4″	7 1/2″	2 1/4″	8 1/4″	2 1/4″	2 1/4″	4 1/4″
Rainfall	98 1/4″	11 1/4″	8 1/2″	7″	8″	6″	4 1/4″	14″

For computing the bearing on subgrade we are furnished a method * by Mr. Thomas H. Johnson, who has made a study of Director Schubert's report with a view to deriving a formula which would show the thickness of ballast necessary to produce an equal distribution of the axle loads on the surface of the roadbed underneath the ballast.

Referring to Fig. 140, the following formulæ are suggested by Mr. Johnson:

$$\text{For gravel, } ab = x = b' + \tfrac{1}{2} d'.$$

$$\text{For stone, } ab = x = b' + d'.$$

The relatively small arcs will approximate to parabolas and may be considered as such.

* Proceedings Am. Ry. Eng. & M. of W. Assn., 1906, Vol. 7.

The intensity of pressures is proportional to the ordinates of the curve.

Areas of parabolic segment = $\frac{2}{3}xy$; hence, mean ordinate = $\frac{2}{3}y$, or mean pressure = $\frac{2}{3}$ maximum pressure, or maximum pressure equal to $\frac{3}{2}$ mean pressure.

Pressure at $b = 0$; hence, to obtain an approximately uniform distribution over the surface of roadbed, the tie spacing S must be such that the curves overlap and have a common ordinate, $y' = \frac{1}{2}y$. This will occur when $db = \frac{1}{4}cb$; or $eb = \frac{1}{4}ab$; or $mo = \frac{3}{4}mn$.*

We should obviously aim to space the tie so that the area of distribution of adjacent ties will overlap and give approximately an equal distribution of the axle loads on the surface of the roadbed underneath the ballast.

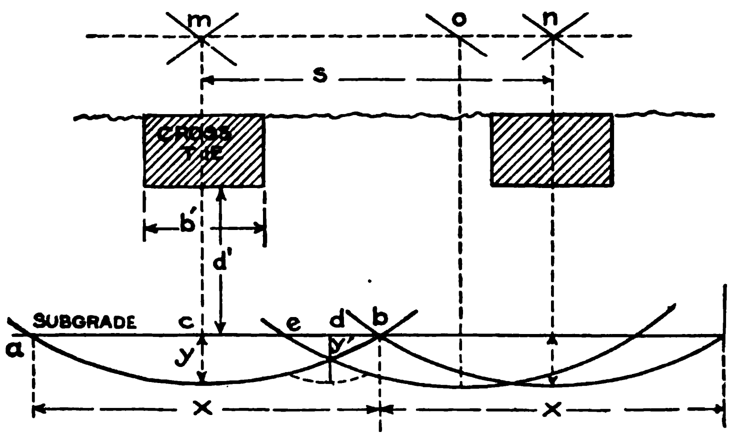


FIG. 140. — Distribution of Pressure to Subgrade. (Johnson.)

With a tie spacing of 23 inches centre to centre of ties, by applying Mr. Johnson's formulæ, we find that it will be necessary to use 45 inches of gravel ballast and 22 inches of stone ballast under the tie to obtain equal distribution on the subgrade.

Tie spacing, $S = 23 \text{ inches} = \frac{3}{4}x.$

For gravel, $S = \frac{3}{4}(b' + \frac{1}{2}d'),$

or $S = \frac{3}{4}b' + \frac{3}{8}d',$

$\frac{3}{8}d' = S - \frac{3}{4}b',$

and $d' = \frac{8}{3}(S - \frac{3}{4}b') = \frac{8}{3}(23 \text{ inches} - \frac{3}{4}8 \text{ inches}) = 45\frac{1}{3} \text{ inches}.$

For stone, $S = \frac{3}{4}(b' + d'),$

or $S = \frac{3}{4}b' + \frac{3}{4}d',$

and $d' = \frac{4}{3}(S - \frac{3}{4}b') = \frac{4}{3}(23 \text{ inches} - \frac{3}{4}8 \text{ inches}) = 22\frac{2}{3} \text{ inches}.$

* Approximate; to be exact, $db = 0.29\,cb$ and $mo = 0.71\,mn$.

It will be seen that unless an excessive depth of ballast is used, a uniform distribution of pressure on the subgrade will not be obtained. However, if the maximum pressure on the subgrade does not exceed its allowable bearing power, the fact that it is not uniformly distributed will not necessarily prove detrimental.

From the above, we see that the maximum pressure = $\frac{3}{2}$ mean pressure; but from article 17 the mean pressure is $\frac{W}{40x}$, and the maximum pressure is, therefore,

$$\frac{3}{2} \times \frac{W}{40x} = \frac{W}{27x}.$$

Substituting the value of x for stone and gravel ballast, we have the maximum pressures:

$$\text{Gravel ballast, } \frac{W}{27(b' + \frac{1}{2}d')}, \tag{1}$$

$$\text{Stone ballast, } \frac{W}{27(b' + d')}. \tag{2}$$

We may take the depth d' for gravel ballast as 18 inches and for stone as 12 inches. Equations (1) and (2) will, therefore, reduce to:

$$\text{Gravel ballast, } \frac{W}{27(b' + 9)}, \tag{3}$$

$$\text{Stone ballast, } \frac{W}{27(b' + 12)}. \tag{4}$$

Equations (3) and (4) are, then, the expressions for the maximum pressure on the subgrade per square inch, in terms of the load on the tie and the width of the base of the tie.

For bearing on clay foundation, subject to frost and usually made ground, 1 to $1\frac{1}{2}$ tons per square foot is good practice. Therefore, putting equations (3) and (4) equal to the bearing power of the subgrade, we can obtain the value of W.

$$\text{Gravel ballast, } \frac{3000}{144} = \frac{W}{27(b' + 9)},$$

$$\text{Stone ballast, } \frac{3000}{144} = \frac{W}{27(b' + 12)}.$$

From which

$$\text{Gravel ballast, } W = 563\,(b' + 9),$$

$$\text{Stone ballast, } W = 563\,(b' + 12),$$

NOTE. — Professor Talbot is now engaged on tests at the University of Illinois having for their purpose the determination of the distribution of pressure in gravel. These tests are not complete, but the evidence produced so far appears to indicate that the pressure under the center of the tie as shown in Fig. 140 is less than that at the edges, due to a distinct arching effect of the material under the tie. A very great difference in the distributing power of the sand was noted under different conditions of dampness. These tests when finished will doubtless furnish information of value in reference to the distribution of the rail pressure to the subgrade.

where W is the safe load in pounds applied to the tie at the rail bearing and b' is the width of the tie at its base in inches.

Table XLVI shows the value of W for the different ties under consideration.

TABLE XLVI. — ALLOWABLE LOAD APPLIED TO TIE AT RAIL BEARING AS DETERMINED FROM BEARING ON SUBGRADE

Width of Tie at Base.	Ballast.		Allowable Load Applied to Tie at Rail Bearing.
	Kind.	Depth below Tie.	
Inches.		Inches.	Pounds.
8	Gravel	18	9,600
9	Gravel	18	10,100
12	Gravel	18	11,800
8	Stone	12	11,300
9	Stone	12	11,800
12	Stone	12	13,500

19. Supporting Power of the Tie

Table XLVII assembles the information given in the previous tables.

TABLE XLVII. — BEARING POWER OF TIES IN THE TRACK

Size of Tie.	7×8 Inches 8 Feet 6 Inches.	7×9 Inches 8 Feet 6 Inches.	7×(6, 12) Inches 8 Feet 6 Inches. (Half Round.)
Allowable load, in pounds, applied at bearing of rail on tie, as determined by:			
Bearing of tie plate,			
Oak	27,000	27,000	27,000
Longleaf yellow pine	17,500	17,500	17,500
Inferior woods	{ 11,000 13,000	11,000 13,000	11,000 13,000
Bending of tie,			
Oak	13,100	14,700	15,000
Inferior woods	9,800	11,000	11,300
Bearing on ballast	13,500	15,000	20,000
Bearing on grade,			
18-inch gravel ballast	9,600	10,100	11,800
12-inch stone ballast	11,300	11,800	13,500

It would apparently seem that the weakest part of the substructure of the track lies in the bearing on the subgrade. In some cases of a very weak subgrade, as in the muskeg swamps of Canada, it has been found necessary to resort to unusual methods of track construction in order to maintain the track in proper condition. Mr. D. MacPherson reported at the January, 1912, meeting of the Canadian Society of Civil Engineers the use of 12-foot ties in a

stretch of track over muskeg, the resulting cheapening in cost of maintenance apparently fully warranted the extra expense of the large ties.

If we consider the effect of the dynamic load, it will be noted from the discussion in the previous articles that the sinking of the tie in the ballast under the action of the dynamic load is little, if any, greater than under the static load, although the dynamic load is from 50 to 75 per cent greater in amount than the static load.

As the calculations of the strength of the track must be made for the greatest load put upon it, which is the dynamic load, it would seem desirable to increase somewhat the safe bearing values given in the table as determined by the bending of the tie and bearing on the ballast and subgrade. We are not warranted, however, in assuming a like increase in strength at the bearing of the tie plate under the action of the dynamic load, as the effect of the moving loads is, in this case, to reduce the strength of the wood.

Examining Table XLVII as it applies to dynamic loading, it is seen that a bearing value of 14,000 pounds, or 7 tons, on half the tie can probably be taken with safety except in the case of the bearing of the plate on the soft-wood tie. The use of a soft wood, as cedar or loblolly pine, for ties under heavy traffic, with the customary form of plate and fastening in use in this country, is to be discouraged, and the general tendency at the present time is to use a wood better adapted to resist mechanical wear under these conditions.

The rail in the track acts as a continuous girder, resting upon yielding supports. Evidently, therefore, not only must the allowable safe load on each tie be determined, but the yielding of the tie under the pressure of the rail must as well be considered.

The relation of the bearing power of the tie to the amount it is depressed in the ballast is not thoroughly understood.

The German engineers, Weber, Winckler, and Zimmerman, have advanced the theory that the pressure, P, of the ballast per unit of surface of the cross tie which it supports is, at each point, in direct ratio with the sinking, Y, of the latter; or $P = CY$ when C is a coefficient depending upon the character of the ballast. The researches of these engineers may be summed up as follows:

(*a*) The results of experiments are stated to agree quite closely with the supposition that the pressure on the unit of surface is in direct proportion with the measure of the sinking.

* (*b*) With a subsoil supposed to be good, the magnitude of the coefficient of ballast has been found: for gravel ballast (without metalled bed) $C = 3$; for

* P in kilograms per square centimeter; Y in centimeters.

gravel ballast (with metalled bed) $C = 8$; for ballast of small stones and scoriæ $C = 5$.

(*c*) The sinking observed under a load in motion, at speeds varying from 40 to 60 kilometers (24.85 to 37.28 miles) per hour, was not much greater than the sinking observed under the same load in a state of repose.

Here again the fact that we are dealing with a dynamic load must be borne in mind, and at high speeds, when the dynamic augment of the wheel load is greatest, the bearing value of the tie corresponding to a given depression in the ballast is largely increased.

The amount the tie is depressed in the track may be judged from the following evidence.

Dr. P. H. Dudley gives from 0.2 inch to 0.4 inch as the amount the general running surface of the rail is below the trackman's surface. Director Schubert states that a wooden tie is depressed from 0.3 inch to 0.4 inch before it reaches a solid bearing. M. Coüard observed that the maximum depression of the tie was about 0.12 inch, and states that the amount of depression is not proportional to the load.

Fig. 130 shows M. Cuënot's tests in which a depression is left under the tie of about 0.04 inch and the loaded tie is depressed about 0.12 inch.

* Fig. 141 illustrates an apparatus used by Bell for measuring and recording the deflection of the rails at various speeds. The following were the results obtained by the passage of a train in which the weights were:

	Tons.	Cwt.
Locomotive, running weight..	46	12
Tender	33	18
Total weight of six carriages.	22	$7\frac{3}{4}$

Speed of Train.	Vertical Deflection.
Miles per Hour.	Inch.
4.2	0.25
14.9	0.25
26.7	0.27
40.4	0.25
57.1	0.33
65.2	0.30

The depression of the tie in the ballast is very erratic. Table LIX shows that in the tests made by the United States government on the depression of

* The Development of the Manufacture and Use of Rails in Great Britain, Bell. Proceedings Inst. of Civil Engrs., Vol. CXLII, April, 1900, p. 133.

rails the mean depression, under the drivers of an engine having axle loads of 44,000 pounds, was as follows:

60-pound rail	.073-inch deflection
70-pound rail	.138-inch deflection
85-pound rail	.233-inch deflection

All of these depressions were obtained in gravel ballast with static wheel loads and give results the reverse of what might have been expected.

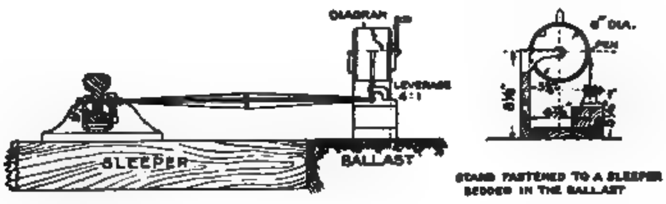


Fig. 141. — Bell's Apparatus for Measuring Depression of the Track.

Fig. 142 shows the relation of the depression to the pressure on the tie. The dotted lines give Zimmerman's coefficients 3 and 8 and the dash line that suggested by Freeman's discussion in Article 21. These curves are straight

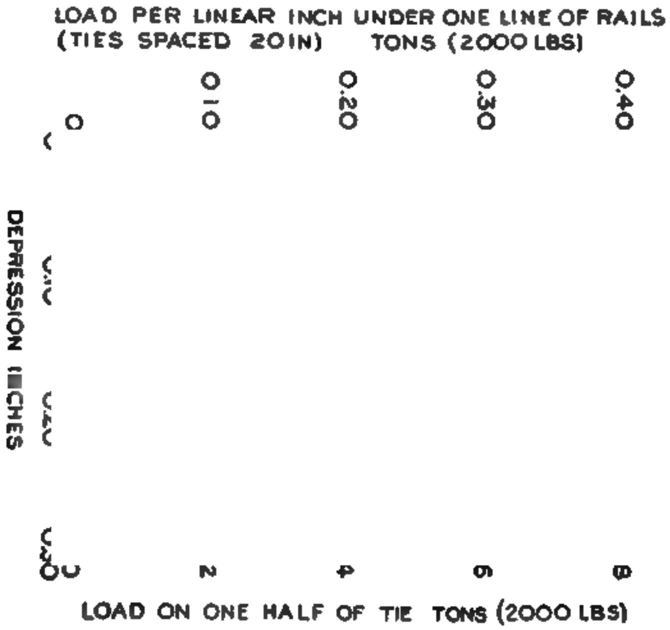


Fig. 142. — Reaction of Tie.

lines plotted through the origin, this appears to be Freeman's assumption, but in the case of Zimmerman's analysis, owing to different parts of the tie depressing unequally, some variation should probably be made from a straight line.

It is quite evident that under the tie at the rail there is formed a depression of ballast, that even under a comparatively light pressure the tie deflects to the depth of this depression, and that from this moment only is the relation of the deflection to the load of importance.

From Mr. Love's analysis of the Government rail experiments (Article 23) we are furnished with a means of determining the relation between the pressure and deflection after the tie comes to a bearing in the ballast. The points plotted in Fig. 142 are obtained from Mr. Love's diagrams and represent the reaction of the tie referred to the depression measured from the highest point in the elastic curve of the rail between two drivers. The tie is assumed to come to a solid bearing at 0.20-inch depression below the trackman's surface.

Bearing in mind that these points are obtained from a static load and that as far as the stresses in the rail are concerned the depth the tie depresses before it comes to a solid bearing is of comparatively small importance, we may construct the curve of pressures shown by the full line in Fig. 142.

It is very probable that what really takes place is shown by the full line in the figure. The rail deflects under light pressures in some cases to as much as 0.20 inch and the tie comes in contact with a compact bed of ballast and the pressure from this point rises very rapidly in proportion to the deflection. In general it was found from the government tests that the ties in the center of the span between the drivers on light rail were supporting very light loads although in some cases they were considerably depressed in the ballast (see Plate XXIII) and for this reason it appeared that a better knowledge of the action of the ballast would be gained by referring the depression to the highest point in the rail between the wheels rather than to the trackman's surface. In the figure the pressure on the tie under the highest point of the rail between two drivers is plotted with a deflection of 0.20 inch below the trackman's surface and all the other deflections in the span referred to this.

Above the limits of the experiments, the curve is flattened to provide for more rapid sinking caused by the increased pressure.

CHAPTER IV

STRESSES IN THE RAIL

20. Stress at Point of Contact of the Wheel with the Rail

Passing from an examination of the external forces acting upon the rail to a consideration of the resulting stresses they produce in the material of the rail, let us first examine the stress at the point of contact between the wheel and the rail.

The essence of the wheel is that its theoretical bearing surface shall be a mathematical line or point, affording no area of bearing surface whatever. In practice this is not strictly the case, owing to the elastic compressibility of the surface, but the bearing surface is always very small, nor can it be increased to advantage by making either the wheel or bearing surface more compressible. To such bearing surfaces the ordinary compression moduli of the textbooks have no application, as they are derived from experiments upon prisms which have the same bearing surface as the greatest section, or nearly so.

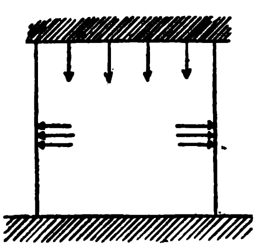


Fig. 143.
Condition of Free Flow.

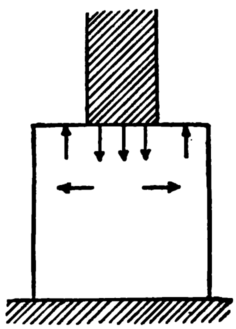


Fig. 144.
Partially Restricted Flow.

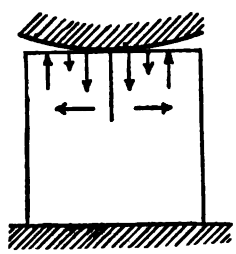


Fig. 145.
Restricted Flow.

Compression Moduli. (After Johnson.)

* When a plain cylindrical column is subjected to a uniform compression stress over its entire cross section, as in Fig. 143, it may be said to be in a condition of "free flow," since it is free to spread in all directions throughout the length of the column. In Fig. 144 the material is compressed uniformly over a small area, as with a die. Here there is a flowing of the metal laterally, and

* Paper contributed by Professor Johnson to the Engineers' Club of St. Louis, December, 1892.

then vertically, finding escape around the edges of the die. This is a condition of confined or restricted flow, and evidently the elastic limit here will be much higher than with the simple column.

In Fig. 145 the surface is compressed by a cylinder, the greatest distortion being at the middle of the area of contact. When this metal is forced to move, or flow, it can find escape only out around the limits of the compressed area. But at these limits the metal is very little compressed, and, hence, must be moved from the center. The confined ring of metal inside the limits of external flow is now much wider, and, hence, the resistance to flow much greater, so that this condition will be found to have a higher elastic limit stress than that shown in Fig. 144, and very much above the ordinary "elastic limit in compression" which is found for the free-flow condition of Fig. 143.

A careful set of experiments was made by Professors Crandall and Marston* to determine the elastic limits of steel rollers on steel plates. In these experiments eleven rollers were employed, from one inch to 16 inches in diameter, with pressures varying from 1000 to 14,000 pounds. Their results showed that the elastic limit load with soft steel rollers on steel plates per linear inch is

$$P = 880\ D,$$

where P = load in pounds per linear inch of roller,

D = diameter of roller in inches.

Professor Johnson† experimented to determine the area of contact between locomotive and car wheels and rails. Sections of wheels were mounted in a 100,000-pound Riehlé testing machine and short sections of rail were placed in the machine so that the wheel treads rested upon them in a normal position. They were then loaded with 5000-pound increments from 5000 to 60,000 pounds, the area of contact being measured after each loading. These actual areas of contact are given two thirds actual size in Fig. 146, and in Fig. 147 the areas are plotted with the area of contact as abscissa and the loads as ordinates.

Professor Johnson states that no permanent distortion was noted upon either rails or wheels at the contact surface up to the 60,000-pound limit. It is seen from Fig. 147 that these areas plot practically upon a straight line through the origin, indicating that the area is directly proportional to the load. This being true, it must follow that the load divided by the area of contact, or the average stress per square inch over the area of contact, is a constant for all loads. This constant is something over 80,000 pounds per square inch.

* Friction Rollers by C. L. Crandall and A. Marston. Trans. Am. Soc. of Civil Engrs., August, 1894, Vol. XXXII, pp. 99–129.

† Discussion of Crandall and Marston's paper on Friction Rollers. Trans. Am. Soc. of Civil Engrs., September, 1894, Vol. XXXII, pp. 270–273.

* Mr. Fowler, in his experiments on the relation of the load on the wheel to the area of the spot, found:

Load on Wheel.	Area of Spot.
Pounds.	Square Inch.
6,000	0.11
10,000	0.12
11,500	0.13
14,500	0.15
16,500	0.17
17,500	0.18
19,000	0.19
25,000	0.20

The following conclusions are drawn by Mr. Fowler from tests on the contact areas between wheels and rails: † That the average pressure on the metal in wheel and rail is within the safe limits at low loads, but at a load of 20,000 pounds the elastic limit is reached and permanent set begins in the rail;

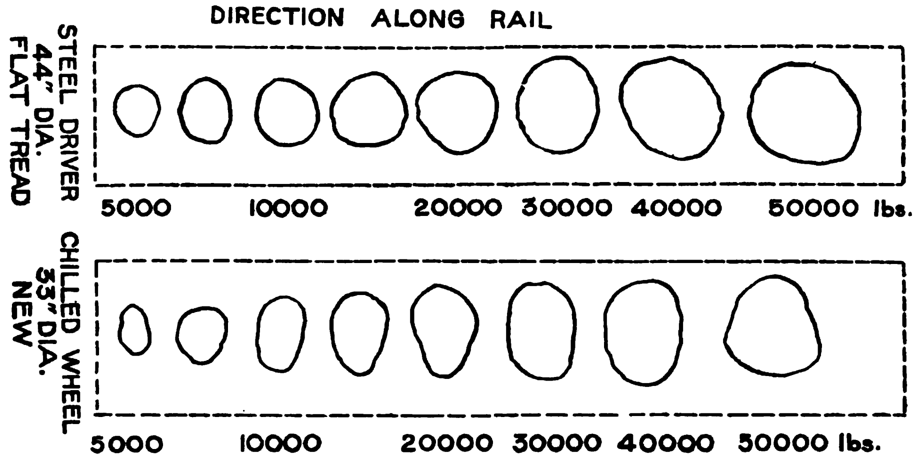


Fig. 146. — Area of Contact between Wheel and Rail. (Johnson.)

that the accumulated pressure at the center of the contact area is excessive with comparatively small loads, and is only prevented from doing injury by the support of the surrounding metal; that the effect of difference in diameter in wheels under the same load is insignificant and only appreciable when the difference is great; that a hard and unyielding cast-iron wheel damages the rail more than a steel wheel, and the wear of the rail will be greater with cast-iron than with steel wheels.

* Proceedings Pittsburg Railway Club, November, 1907.

† Bulletin of the International Railway Congress, London and Brussels, 1908, pp. 651–663. G. L. Fowler, Contact Areas between Wheels and Rails. See also G. L. Fowler, The Car Wheel 1907, p. 161. Giving the results of a series of investigations made for the Shoen Steel Wheel Co.

* Hönigsberg describes a method proposed to be applied to measure the actual forces between the wheel and the rail. This is based on the fact that polished surfaces of iron or steel show peculiar markings — sometimes known as Lüder's Lines — on the limit of elasticity being exceeded. As the limit of elasticity can be artificially raised to any value between the primitive elastic limit and the breaking strength, this gives a means of making standard test

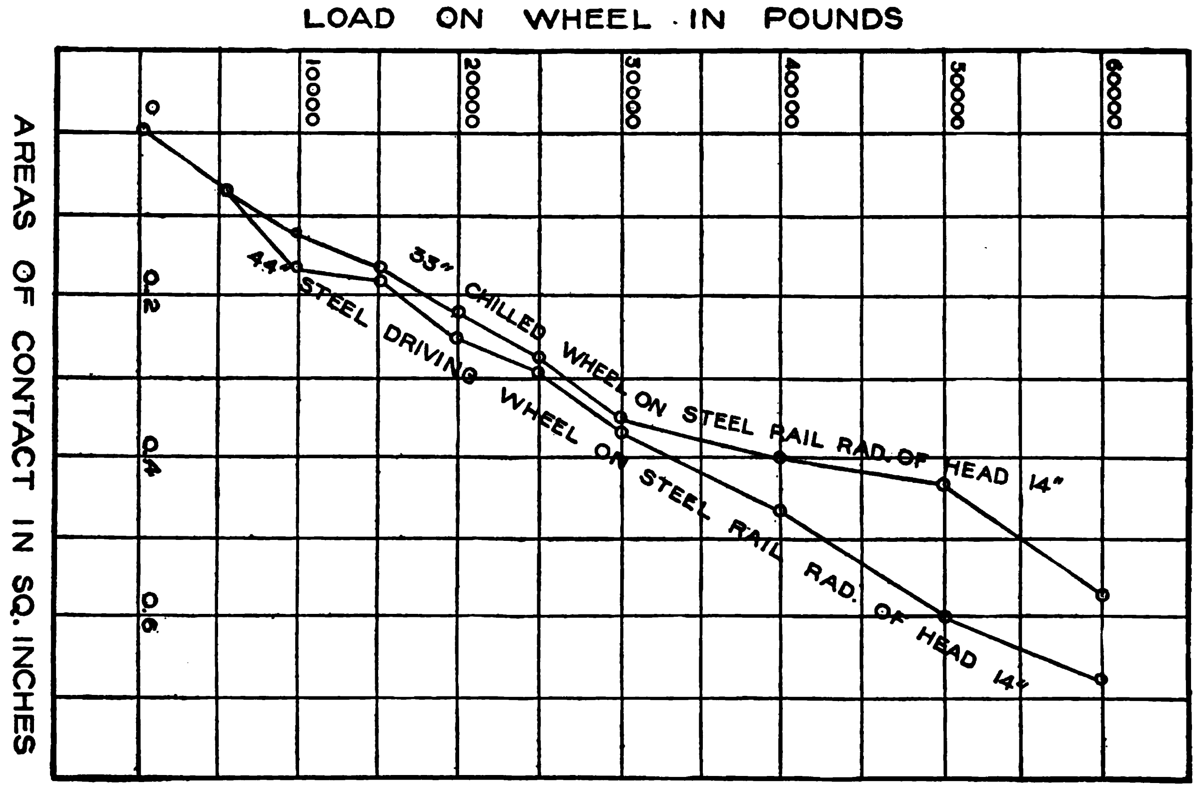


Fig. 147. — Relation between Areas of Contact and Load on Wheel. (After Johnson.)

pieces; since when lines appear it may be concluded that the artificially raised limit has been exceeded.

If a wheel passing over two calibrated pieces of metal causes the lines to appear on one and not on the other, it may be concluded that the actual stress caused by the wheel lies between the elastic limits of the two standard pieces.

Tire wear would seem to indicate that the elastic limit of the metal was exceeded or too closely approached. The investigation of a committee of the Master Mechanics Association in 1895, on the wear of locomotive tires, has thrown interesting light on this subject.

* Measurement of Forces between Rail and Wheel. O. Hönigsberg, Organ für die Fortschritte des Eisenbahnwesens, Wiesbaden, 1904, pp. 109–160.

* Fig. 148 shows a diagram of the average wear of the tires of the fifty-three ten-wheel engines for which the calculations plotted in Fig. 7 were made, and Fig. 149 shows the same data of the eight-wheel engines shown in Fig. 6.

The lower diagrams in Figs. 148 and 149 show the ratio of the rotative force to the weight on the rail, which we may call the "coefficient of slip." Since the coefficient of slip is the rotative force at the rail divided by the total weight of the drivers on the rail, it is evident that as this coefficient increases the tendency of the drivers to slip increases, and when it just equals the coefficient of friction between the tire and rail the engine is on the point of slipping.

The committee of the Master Mechanics Association in its report says:

An examination of the tire wear shown in Figs. 148 and 149 shows no distinct relation between the worn spots and the curves of maximum pressure of the wheels as given in Figs. 6 and 7. A very clear relation can, however, be traced between the worn spots and the parts of the wheel where the greatest coefficient of slip is combined with the heaviest wheel pressure.

Local peculiarities of the tire, such as soft spots in it, as well as flat spots caused by slight sliding, affect the final contour of the worn tire, and it is only by taking the average wear at the same point on a large number of tires that the irregularities due to general conditions show themselves with the necessary clearness.

Referring to the diagram of the average wear of the tire of the fifty-three ten-wheel freight engines shown in Fig. 148, first we will consider the wear of the front and back tires only, as these wheels were overbalanced, the main wheels being underbalanced, and, on account of the effect of the angularity of the main rod, subject to quite different conditions from the others.

Directing our attention to the wheels on the right side of the engine, an inspection of the figure shows quite uniformly, in both right forward and back tires, two locations of maximum wear, one beginning at about 160° and attaining its maximum at 220° or 230°, the other becoming pronounced at about 10° or 20° and attaining its maximum at about 50°. It will also be noticed that both of these low spots are connected from 220° to 50° in the direction of rotation by a portion of the tire much more worn than that portion from 50° to 220°.

To understand the cause of this irregular wear, it is necessary to bear in mind that there are at least two ways in which driving wheels are slipped: first, when the slipping is slightly but distinctly noticeable, extending through but a small portion of the revolution; second, when the hold on the rail is entirely

* Proceedings Am. Ry. M. Mech. Assn., Vol. 28.

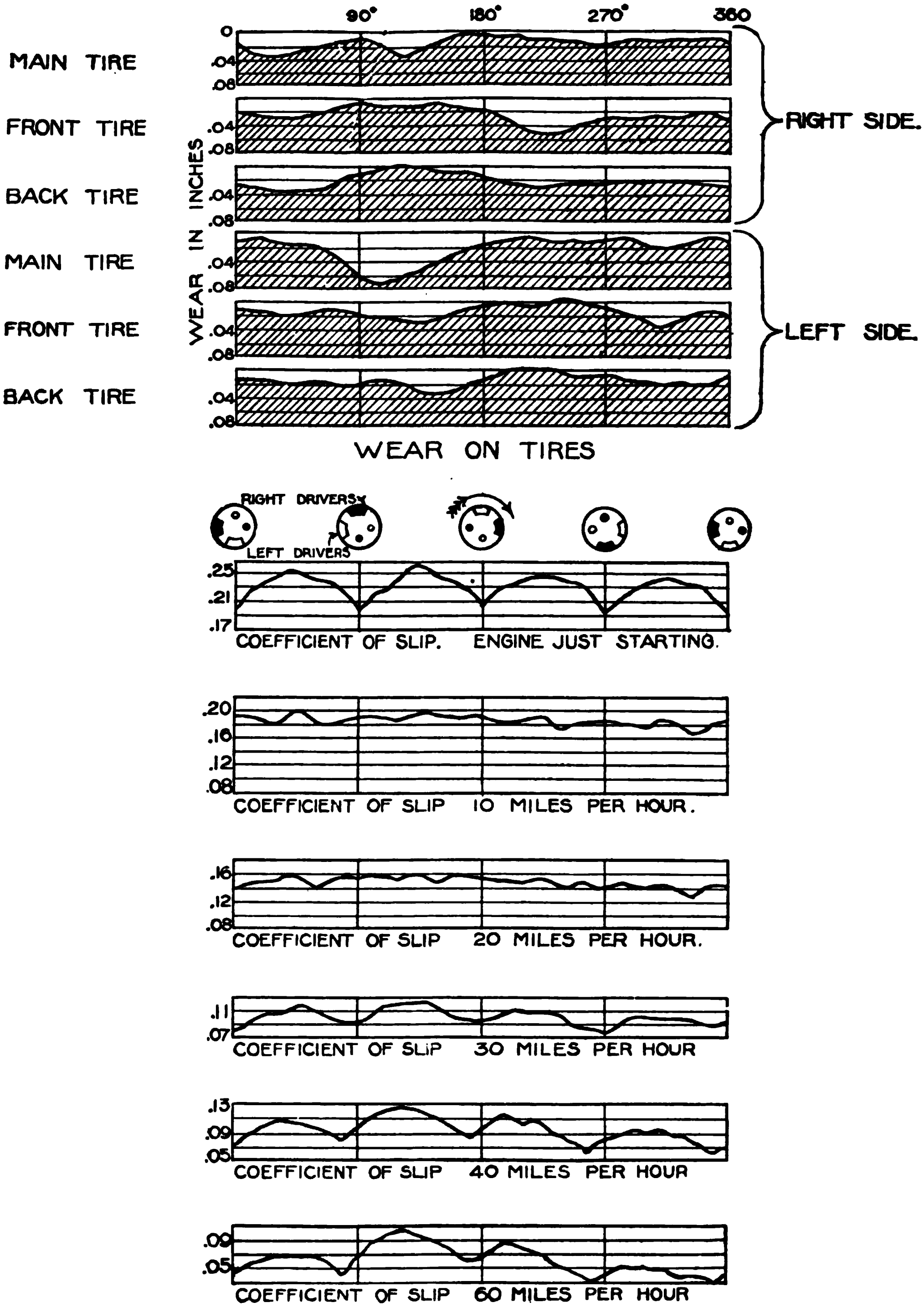


FIG. 148. — Tire Wear, Ten-wheel Engines. (Am. Ry. M. Mech. Assn.)

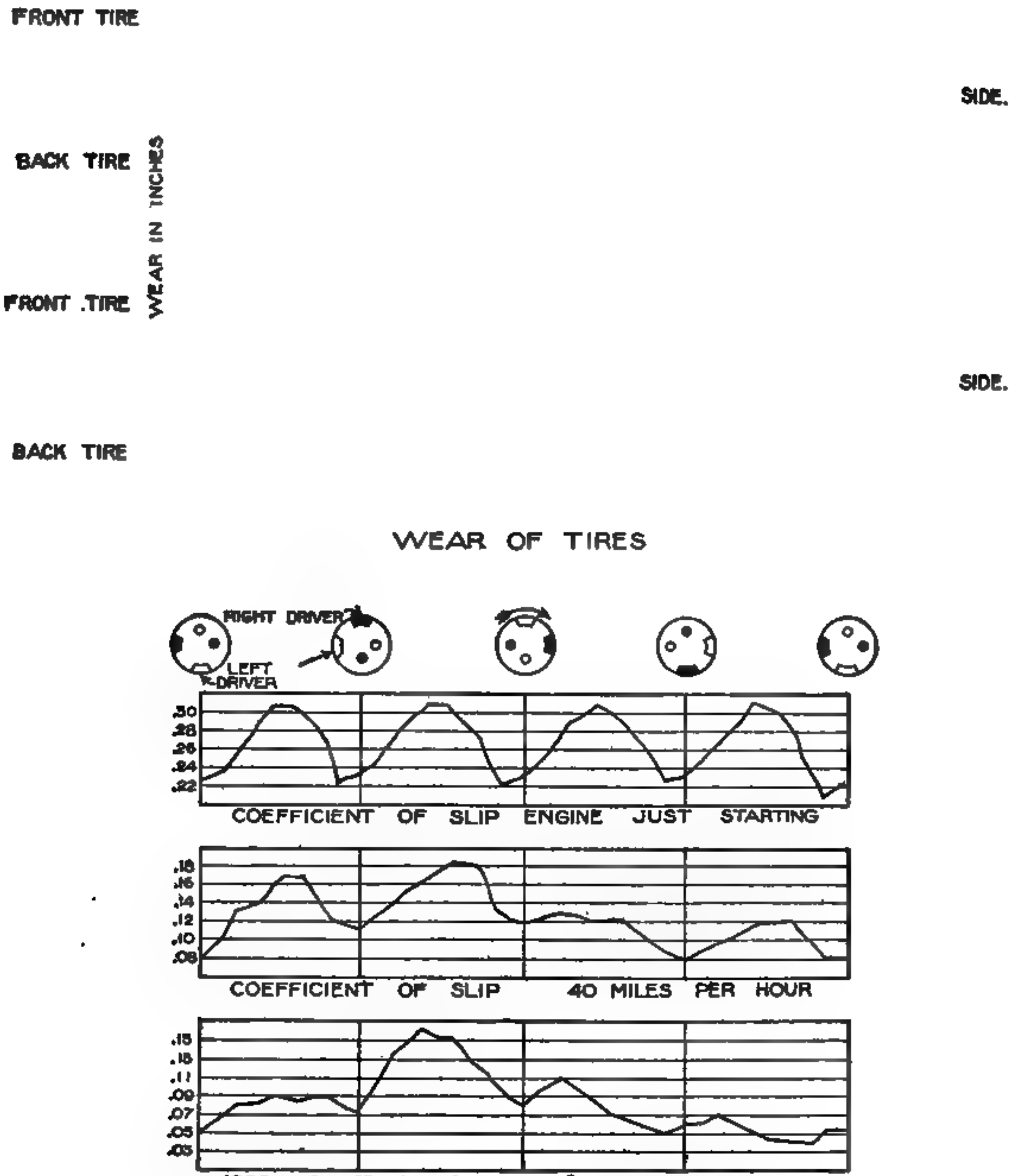


FIG 149. — Tire Wear, Eight-wheel Engines. (Am. Ry. M. Mech. Assn.)

broken, and the wheels slip through a number of revolutions, usually turning with considerable velocity.

The first case, of slipping through but a small part of a revolution, occurs almost without exception on heavy pulls at slow speed, often being seen when an engine is pulling hard on a hill with just enough sand being used to avoid serious slipping, but not enough to prevent a slight slip at points where the rotative force is the greatest. The beginning of slip must occur under these conditions at or near the maximum of the coefficient of slip. Referring to Fig. 148, we find a maximum value of the coefficient of slip at 40° to 50°, and 130° to 140° with engine just starting. At 20 miles per hour, the maxima are at 40° and 130°, and at this speed the tendency to slip at 100° is also almost as great as at the other points. The figure shows a small spot following 100° on the front tire, but none is seen on the back. The diagrams on Fig. 7 indicate the cause, as the pressure of these wheels upon the rail at 100° is almost at a minimum and is much less than at 140° to 160°.

It is also noticeable that the amount of wear following 160° is greater than that following 40° or 50°, for the same reason. This variation in pressure upon the rail increases rapidly with the speed, and Fig. 7 shows very clearly that following 40° the pressure of the front and back wheels on the right side decreases very rapidly, while the reverse is the case following 160°.

The same conditions as to pressure on the rail occur, for the left-hand front and back wheels, just 90° back of those on the right side, and irregularities of wear produced by the drivers slipping through a number of revolutions at considerable velocity should occur on the left wheels at points 90° back of the corresponding point on the right wheels: 90° back of 40° is 310°, and 90° back of 220° to 230° is 130° and 140°. Fig. 148 shows the greatest depth of wear of tires of the left front and back wheels to be almost exactly at these points. There is also a small spot worn at 40°, due to the slipping at slow speeds when the influence of the counterbalance is nil.

The irregularities of wear of the main wheels follow the same law as those of the front and back wheels, but the conditions are considerably modified by the difference in pressures caused by the influence of the angularity of the main rod, and to a less degree from these wheels being under- instead of over-balanced.

The spots caused by the slight slipping at slow speeds at about 40° and 130° should be found in these wheels as in the front and back wheels, unless the accompanying condition of necessary pressure is absent. Fig. 7 shows from 16,500 to 17,000 pounds at 40° on the right main wheel, and from 12,700 to

17,500 pounds on the left wheel at the same point, indicating greater wear on the right than on the left tire at this point, which the diagram, Fig. 148, shows. The wear at 130° is found in these wheels, but, owing principally to the influence of the angularity of the main rod and partly to the wheels being underbalanced, the conditions of pressure following 130° on the right main wheel are very different from those of the right front and back wheels. Fig. 7 shows that the pressure on this wheel is always rapidly decreasing following 130°, instead of increasing, and, consequently, the worn spot at this point extends but a short distance in the direction of rotation. Not so, however, with the left main tire. Here the pressure is always increasing following this point, and the figure shows the great elongation of this spot in the direction of rotation, extending it as far as 210°, while that on the right tire extends only to 165°.

There still remains to be explained why the heavy spot on the main tire should slightly precede the point of the maximum coefficient of slip at 130°, and why that on the left wheel still farther precedes this point and, in general, is greater than on the right. An inspection of the diagram on Fig. 7 shows that the pressure of the right main wheel on the rail is always greater preceding than following the 130° point. Fig. 148 also shows that the coefficient of slip is high as early as 110° after a speed of 10 miles per hour is attained, and increases but slightly to its maximum at about 130°. Any slipping occurring between 110° and 130° will, on account of the pressure, cause a serious spot at this point on the main wheels, which the diagram shows.

Fig. 148 shows the worn spot under consideration on the left tire, not only elongated in the direction of rotation, which is explained by the difference in pressure in this direction, but also in the opposite direction, extending beyond the 80° point. This is doubtless due to the slight slip caused by the main rod passing the forward center and suddenly thrusting this wheel back an amount equal to the lost motion in the bearing shoe and wedge. The same thing occurs, of course, on the right wheel, and the sharp, but slight, wear following the 350° point shows it quite clearly. On the left wheel, however, this wear is immediately followed by the more serious one due to the approach of the maximum point of coefficient of slip from 110° to 130°, and becoming merged into it, both are increased.

The upper diagram on Fig. 149 shows the wear of the tires on the engine for which the calculations are plotted on Fig. 6 for the eight-wheel engine. This shows in a general way the same characteristics of the average wear for the fifty-three ten-wheelers, shown on Figs. 7 and 148, but is, undoubtedly, affected to a considerable extent by unknowable local conditions. Here the front wheels,

of course, correspond most nearly to the main wheels on the ten-wheeler, and here, as there, the left main tire shows the most serious irregularity of wear.

The committee presented the following conclusions as a result of its investigation, which it should be borne in mind was in connection with much lighter wheel loads than obtain at the present time.

"There is no doubt locomotive tires wear without slipping, and there should be, and probably is, a portion of the irregular wear due to the pulverizing or crushing action being greater under heavy than light loads.

"An experiment was made by removing all the overbalance in the counterbalance of an engine, when the irregularities of wear in the main wheel were almost exactly duplicated in location and to a remarkable degree in magnitude. This, together with similar experiments attended by the same general results, leads us to believe that the irregularities of wear of the tire are almost wholly caused by abrasion from slipping, and that the pulverizing of the steel from pressure alone is of secondary importance."

With the smaller wheels under the cars and locomotive tenders the conditions are quite different.* The smaller steel wheel or tires do not render as satisfactory service under heavy loads and high speed as the larger locomotive tires, principally for the reason that the manufacturer is not able to put into the small tire sufficient mechanical work to obtain uniform physical properties for the full circumference of the tire, and in the service portions of the tread thickness.

The experience with 36-inch steel-tired wheels under locomotive tenders illustrates this point. The steel tender wheels have failed by shelling out, and portions of the metal of inferior physical structure on one-third of the circumference have worn so as to make an eccentric tire which has caused such severe impacts on the rail as to require the removal of the wheels after a short service. The average load on these wheels is 18,000 pounds, and the maximum static load 20,400 pounds; many of them give only six months' service, or 30,000 miles, after a first or second turning.

In a paper read at the last International Railway Congress, published in the Bulletin of October, 1911, Dr. P. H. Dudley has proposed a new method of measuring the tonnage service of rails and wheels. He explains that the tonnage supported by a given portion of the bearing surface of a rail due to a passing wheel is the total load multiplied by the number of wheels passing over it. The tonnage sustained by the metal in the treads of the wheel is the total wheel load multiplied by the number of revolutions, and this tonnage accumulates

* Railway Age Gazette, December 22, 1911.

more rapidly than that of the rail. It is greater also as the diameter is less and the number of revolutions larger, so that the tonnage service of 36-inch tender wheels is much greater than that of the 75- or 80-inch drivers, though the loads on the latter may be much larger.

The pressure and movement of heavy loads on the rail causes a cold rolling to take place on the head of the rail, which tends to expand the metal and, if the rail were free to move, would cause it to assume a curved form with the head on the convex surface.* As the rail cannot bend, this cold-rolled metal is subjected to a compression stress. A tensile component would be expected in the vicinity of and next below the part which was affected by compression strains, and this has led to a theory of the cause of the oval silvery spots or transverse fissures in the head of the rail observed by Mr. Howard.† These rail fissures which resemble the smooth surfaces of a progressive fracture have so far been largely confined to one steel company. The theory advanced as to their probable cause should not be regarded as final until further substantiated, and many engineers feel that it is not the true explanation. No other adequate reason has been offered as yet to explain their formation, although a careful investigation is being made which will doubtless throw further light upon the subject.

Mr. Howard ‡ states that: "The flow of the metal of the head, apparent to the eye and witnessed very generally in portions of the track, may be taken as evidence of exhausted ductility of the metal. The ability of the steel to elongate, as found in the primitive state of the rail before going into service, is lost by reason of its development, and the rail, at first tough and capable of being bent, is now brittle and will bend only to a limited extent before rupture.

"The brittleness is due to the flow of the metal at or immediately below the running surface of the head. The structural continuity has not been destroyed, as may be shown upon annealing the metal, which effects a restoration in its ability to elongâte. A rail from service will not bend well with the head on the tension side, since the surface metal has been subjected to cold flow in advance of its being worn away by abrasion."

* Mr. Howard found that in the case of a rail, exposed to this action, on cutting off the head from the web, the former sprung into a curved shape with the running surface on the convex side. The deflection at the middle of the length of the piece, 5 feet long, was 0.20 inch. It is probable, however, that some of this curvature was caused by the strains set up in the rail when cooling.

† Appendix to Report by the Interstate Commerce Commission on Accident to a Lehigh Valley Railroad Train at Manchester, N. J., on August 25, 1911. See also Broken Lehigh Valley Rail, Iron Age, Vol. 88, Part 2, p. 800.

‡ Some Causes Which Tend toward the Fracture of Steel Rails. James E. Howard, Journal Association of Engineering Societies, July, 1908.

Removing the surface metal, in the planer, restores the bending qualities of the rail, but in this case it is necessary to plane away the metal from the sides as well as from the top of the head, that is, as far down as the cold flow has taken place.

The difference in the bending qualities of the same rail according to the head being on the tension or compression side is shown by Fig. 150. The

FIG. 150. — Two Pieces of a Worn 100-lb. Rail after Testing. The upper piece, with head on compression side, bent 21 degrees without rupture. The lower piece, with head on tension side, bent 4½ degrees and then ruptured. (Howard.)

upper piece of rail in the figure was bent with the head in compression, while the lower one had the head on the tension side of the bend.

Rails of this series of tests have ruptured with a deflection of only 3 to 5 degrees when the head was in tension, but remained unruptured when bent through an angle of 20 degrees or more with the base in tension. After annealing these old rails, of exhausted toughness, the bending qualities were restored, after which the rail could be bent in either direction through about the same number of degrees without fracture.

The effect of the exhausted metal in the head is well illustrated by Table XLVIII, which presents some of the results of Kirkaldy's tests on rails. * Kirkaldy states that "the rail appears to have been gradually hardened under the action of the traffic, more especially on the immediate skin or surface, until the steel thereon cracked under the upward flexion of the rail in the regions just over the chairs, or the minute cracks may have been induced by the severe action of the brakes on trains, so to speak, tearing up or disintegrating the surface of the steel."

TABLE XLVIII. — BENDING TESTS ON WORN RAILS. (Kirkaldy.)
(Distance between supports 5 feet, load applied at center)

Description.	Weight per Yard.	Dimensions.		Stress.		Deflection.		Remarks.
		Depth.	Web.	Elastic.	Ultimate.	At 40,000 Pounds.	Ultimate.	
	Pounds.	Inches.	Inch.	Pounds.	Pounds.	Inch.	Inches.	
Worn rail; 80 lbs. main line, 23 years' service.	77.62	5.00	.65	35,700	60,780	0.62	8.0	Removed uncracked.
Same, tested inverted.				35,800	58,240	0.59	4.19	Snapped.
New rail.	85.41	5.50	.68	44,300	78,840	0.26	8.0	Removed uncracked.
Same, tested inverted.				43,500	77,350	0.28	6.5	Removed buckling.
Worn rail; 85 lbs., in road 5 years with heavy wear.	84.25	5.43	.68	47,800	86,710	0.24	8.0	Removed uncracked.
Same, tested inverted.				47,800	88,130	0.24	6.5	Removed buckling.
Worn rail; 82 lbs., 10 years, service.	75.00	4.95	.66	40,000	73,130	0.31	8.0	Removed uncracked.
Same, tested inverted.				40,000	55,260	0.31	1.44	Snapped.
Worn rail; exposed to brake action.	74.70	4.86	.66	35,400	61,440	0.64	7.0	Removed uncracked.
Same, tested inverted.				31,500	35,400	....	0.36	Snapped; slight flaw.

The slipping of the driving wheel of the locomotive when starting a train may cause roughness of the metal of the rail, accompanied by intense heating of the immediate surface metal of the head. In addition to the loss in ductility of the steel by reason of its flow under the wheel pressures, the metal at the running surface is hardened through this action of the wheel. Showers of sparks attend instances of this kind, from which the high temperature acquired by the particles of the steel may be judged of. There follows also a sudden reduction in temperature through conductivity of the cold metal below, which has an effect similar to quenching steel from high temperatures in water or other quenching liquids, and there results a surface hardening of the metal. During this period of hardening the surface metal is placed in a state of intense tension, relief from which is obtained by the development of cracks in the steel.

A very interesting experiment is reported by Wickhorst † on the flow of metal in the rail head under the wheel load. The test was made to determine,

* Kirkaldy on Effects of Wear upon Steel Rails, Appendix II. Min. of Proceedings of the Inst. of Civil Engrs., Vol. CXXXVI, January, 1899, p. 166.

† Flow of Rail Head under Wheel Loads. M. H. Wickhorst, Proceedings Am. Ry. Eng. & M. of W. Assn., 1911, Vol. 12, Part 2, p. 535.

if possible, what change is made in the microstructure of the head of the rail by the rolling over the rail of heavy wheel loads. At the same time, measurements were made of the spread of the head and the width of the bearing produced.

The test was made on a new 70-pound Bessemer rail with a reciprocating machine in which a piece of rail is moved back and forth under a wheel to which a load can be applied by means of levers. A diagram of the machine is shown in Fig. 151, from which it is seen that the rail is fastened to a steel bloom

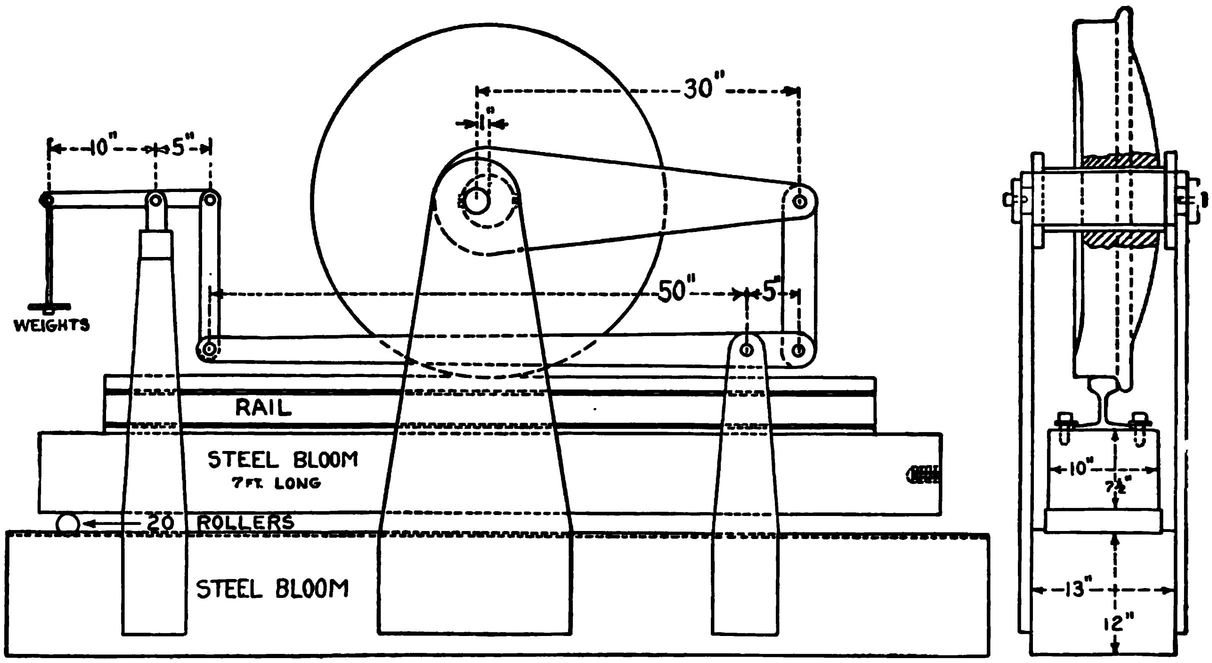


Fig. 151. — Reciprocating Machine for Testing Flow of Metal in Head of Rail. (Am. Ry. Eng. Assn.)

which runs on rollers running on another steel bloom that forms the bed of the machine. The rail bed is connected by means of a connecting rod to the bed plate of a planer, which furnishes the power to run the rail machine. The weights applied to the weight hanger are multiplied 600 times, as applied to the axle of the wheel. The piece of rail tested was 12 inches long, which was set up between two other similar pieces, which acted as end pieces onto which the wheel could roll when leaving the piece under test. The piece tested had the sides of the head planed vertical to a width of head of 2 inches. This width was used partly to accentuate the test and partly to do away with the rounded corner, so as to allow of measuring the width closer to the top of the head, and the sides were made vertical so the measurements could be made satisfactorily with a micrometer along the whole depth of the head. The section of the

original rail and as tested are shown in Fig. 152. Before testing, the width of the head was determined at the top, at the bottom and halfway between, both at the middle of the piece tested and at one end, by means of a micrometer. To determine the sag of the head, two prick-punch marks were put on each side of the rail at the middle of its length, one on the side of the head near its bottom and the other on the top side of the base, about ¾ inch from the web. In order to have a vertical side on which to prick-punch the mark, the base was gouged at the desired place. The distance between the marks was measured in .01

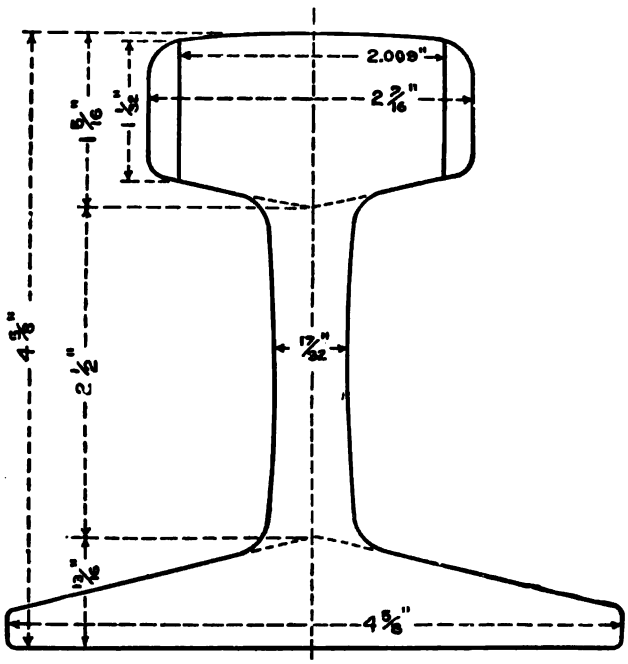


Fig. 152. — Section of 70-lb. Bessemer Rail Tested for Flow of Head. (Am. Ry. Eng. Assn.)

inch by means of a fine-pointed toolmaker's dividers and a steel scale reading to .02 inch.

The test was started with a load of 30,000 pounds applied to the wheel, using 1000 double strokes or 2000 rollings of the wheel over the rail under test. The bearing assumed a width of .64 inch. The only effect on the width of head was to spread the top of the head .002 inch, and the load was, therefore, increased at once to 60,000 pounds and the test continued until the head seemed to no longer spread as measured with the micrometer. The width of the head of the rail and the width of the wheel bearing on the rail, at various stages of the test under the load of 60,000 pounds, are shown in Table XLIX. The spread of the top part of the head and the width of bearing in this table

includes also the effect of the preliminary rolling of 2000 wheel applications with 30,000 pounds. The head did not show any sag throughout the test.

TABLE XLIX.— ROLLING TESTS ON RAIL HEAD WITH LOAD OF 60,000 POUNDS

Wheel Rollings.	Width of Bearing.	Spread of Head.					
		Middle of Rail.			End of Rail.		
		Top of Head.	Middle of Head.	Bottom of Head.	Top of Head.	Middle of Head.	Bottom of Head.
200	.92	.002	.000	.000	.004	.002	.000
2,000	.92	.009	.003	.000	.006	.002	.000
4,000	.94	.010	.004	.001	.006	.002	.000
23,460	1.02	.013	.006	.001	.008	.003	.000
32,142	1.04	.013	.006	.001	.008	.003	.000

It should be remarked that the wheel was beveled some, and the bearing was, therefore, on one side of the top of the head, remaining throughout about .2 inch from one side and increasing in width toward the other side.

A microscopic examination was made of the rail at the top of the head and at the center of the head both before and after rolling. While the micro-photographs obtained indicated a slight stratification of the grains in a longitudinal direction, there was little, if any, difference between the specimens before and after rolling. The material tested was good ductile material of medium hardness for rail steel, and as the maximum lateral stretch at the top of the head was only .013 inch, much difference in the microstructure could hardly be expected.

It is evident that the metal in the head of the rail must have a high elastic limit to successfully meet the severe conditions of modern service. This fact was clearly brought out several years ago by one of the writers in connection with some service tests on annealed rails on the Philadelphia and Reading Railway. An account of this investigation appears in the Proceedings of the New York Railroad Club, December, 1906. Eleven 90-pound rails were sawed into halves, and one half of each rail was annealed. The carbon content averaged 0.54 and the manganese 1.06 per cent. After 88 million tons traffic it was found that the annealed rails averaged 31.9 per cent more wear and they also showed a greater tendency to crush and splinter, but it was found on test that the elastic limit had been reduced over 10 per cent. The annealed rails, in spite of their finer structure and consequent greater toughness, did not wear so well on account of the lower elastic limit.

In Article 9 attention was called to the effect of the inertia of the track on the stresses produced by impact, and in Article 8 it was shown how the lack of round-

ness of the wheel may cause excessive strains in the running surface of the head. These factors make it much more difficult to control this stress than that produced by bending; in the latter the forces acting on the rail can be determined within closer limits and the remedy is easier to apply.

The rail is in fact called upon to perform two quite distinct functions, one of which is to resist the strain produced at the area of contact between the wheel and the rail and the other to resist the bending stress; the latter can be reduced by increasing the moment of inertia of the section or strengthening the track structure, but the former is in a measure independent of the form of the rail and requires a change in the character of the material of which the rail is composed.

The defect known as "roaring rails" is caused by an imperfect surface or corrugations in the head of the rail. These corrugations are confined almost exclusively to the rails used on electric roads and few problems, confronting the maintenance of way engineer of such roads, have attracted the attention and study being given to this trouble.

There are many conflicting opinions as to the cause of the phenomena, none of which appear adequate to properly explain it.*

The corrugations of rails in recent years have increased rapidly in number; once they start they rapidly grow worse and it is important to remove them as soon as the indentations appear. This is generally accomplished by means of a rail grinding device which consists either of a carborundum block rubbing over the rail or an emery wheel which grinds the rail to a true surface.

The cost of removing corrugations in rails varies from a few cents to 50 cents per foot of rail, depending on the depth of the waves; fortunately after the corrugations have been removed there is little probability of their ever returning.

* Some of the recent literature on this subject is as follows:

Andrews, J. H. M. — Some notes on rail corrugation. 1500 w. 1910. (In Electric Railway Journal, Vol. 36, p. 370.)

Outlines prominent causes of corrugation and presents a few notes and conclusions.

Busse, A. — Rail corrugation. 1500 w. 1910. (In Electrician, Vol. 65, p. 930.)

Observations from many points indicate strongly that corrugation is due primarily to defects in the rail metal, resulting from the rolling.

Panton, Joseph A. — Rail corrugation. 26 p. Ill. 1907. (In Journal of the Institution of Electrical Engineers, Vol. 39, p. 3.)

Concludes, in summary, that corrugations are caused, directly or indirectly, by lateral play in weak trucks, the weakness being intensified by unsymmetrically driven axles.

Wilson, C. A. Carns. — Rail corrugation. 3000 w. Ill. 1908. (In Engineering, Vol. 86, p. 90.)

Aims to show conditions under which corrugations are produced.

21. Proposed Solutions of the Bending Stress in the Rail

Following the path of the forces as they pass through the rail and are distributed to the ties, we find very complex and unstable conditions. The rail is supported on a series of yielding supports. These supports, through their unequal yielding, bring about distributions of stress in the rail that are difficult to calculate.

Before proceeding further with the discussion of this subject, let us turn to some of the methods advanced for the proper solution of the problem.

* Mr. O. E. Selby approaches it in the following manner: " Examining first the bending stress in the rail, we have 50,000-pound axle loads on supports 20 inches apart. For these conditions the American Railway Engineering and Maintenance of Way Association specifications for steel bridges, paragraph 5, call for 100 per cent impact, making the stresses equivalent to those from a 100,000-pound axle load, or a 50,000-pound wheel load.

" For a simple beam the bending moment in one rail would be 250,000 inch-pounds. For a continuous beam with rigid supports, it would be two-thirds that, and for a continuous beam with partially yielding supports, three-fourths of the bending moment for a simple beam is reasonable, giving 187,500 inch-pounds. If we consider the wheel placed over a tie which yields enough to carry one-fourth of the load to each adjacent tie, the resulting moment in the rail is the same. The section modulus of an 80-pound A. S. C. E. rail is 10.0, making the extreme fiber stress 18,750 pounds per square inch. For a 100-pound rail the unit stress is reduced to 12,800.

" Passing to the load on the tie, we encounter an element which must vary between rather wide limits with the stiffness of the rail and yielding of the supports. With a simple beam and load placed midway between the supports, the reaction on each support would be one-half the load. The theory of the continuous girder would make the reactions about 55 per cent to 67 per cent, depending on whether the load is placed over a support or midway between.

" The yielding of supports would undoubtedly reduce these percentages. Bridge specifications usually consider the load equally distributed among three ties, but bridge ties are spaced usually 14 inches between centers, so that, if the load going to one tie is proportioned to the tie spacing, the amount for 20-inch spacing would be $20 \div 14 \times 1 \div 3 = 20 \div 42 = 47.6$ per cent. There-

* O. E. Selby, Bridge Engineer, C., C., C. & St. L. Ry. A Study of the Stresses Existing in Track Superstructures and Rational Design Based Thereon. Proceedings Am. Ry. Eng. & M. of W. Assn., 1907, Vol. 8.

fore, the assumption that the maximum load on a tie is half the axle load seems a proper one.

"Modern specifications call for an E-60 loading, which contains 60,000-pound axle loads, spaced 5 feet between centers. A tie spacing equal to one-half the wheel spacing would load the girder (rail) at the quarter points and produce moments (in a simple beam) equal to those produced by a uniform load.

"A more practicable tie spacing, one-third of the wheel spacing, would similarly produce moments $\frac{1}{72}$ part, or only 1.4 per cent greater than those from a uniform load, so that if we design a rail for a uniform load equal to the wheel load divided by the wheel spacing, the result would be very nearly correct. The wheel load with impact is 60,000 pounds, or 1000 pounds per linear inch of rail. For a continuous beam (indefinite number of spans and loads) the maximum moment ~~movement~~ is $1 \div 12 \times WL^2 = 1 \div 12 \times 1000 \times 60^2 = 300,000$ inch-pounds."

The following has been presented by Mr. Bland:*

"The rail acting as a beam under passage of wheel loads is in a condition of 'restrained' ends, and the maximum moment from a wheel load Q is given by $M = \pm \frac{1}{8} Ql$, 'Q' being concentrated load and 'l' being span center to center of ties. The moment alternates from positive to negative, and alternates equally. The dynamic augment to static wheel load is taken 60 per cent for a speed of 75 miles per hour.

"Assume a static axle load of 60,000 pounds, giving static wheel load of 30,000 pounds. The dynamic augment for 75 miles per hour is 60 per cent, making a dynamic wheel load of 48,000 pounds."

TABLE L. — RAIL STRESSES. (Bland.)

Rail Weight.	Tie Spacing, c. to c. $= l$.	Minimum Rail Modulus $= Z$.	Dynamic Moment.	Resulting Unit Stresses.
Pounds per Yard.	Inches.		Inch-pounds.	Lbs. per Sq. In.
60	24	6.70	144,000	21,500
70	24	8.30	144,000	17,350
85	22	11.30	132,000	11,680
100	22	15.00	132,000	8,800

The following investigation of the stresses in the rail was suggested by Mr. F. B. Freeman, in a paper presented to the New York Central Lines Maintenance of Way Committee entitled "Investigation of Stresses in Track Superstructure." This paper is of considerable interest, as the results obtained by

* J. C. Bland, Engineer of Bridges, Penn. Lines West of Pittsburg, on the Capacity of Modern Heavy Rail for Existing Heavy Engines, 1907.

the methods proposed are compared with the stresses actually given by test of the rails under the moving trains. An abstract of the paper follows:

By means of plotted curves recently published showing resultant wheel loads in terms of the unit static loads at various speeds, Dr. P. H. Dudley shows as a result of his experiments that with smooth wheels rolling without acceleration, the impact approaches 50 per cent as a limit at 100 miles per hour. A curve of resultant wheel loads at various speeds with acceleration shows 100 per cent impact as the limit at 100 miles per hour. At speeds of 50 to 70 miles per hour the impact appears to be about 75 per cent when the train is under acceleration.

By acceleration it is meant that the locomotive is exerting its maximum tractive effort at that speed.

From his stremmatograph tests, Dr. Dudley finds that the maximum extreme fiber stresses in the 100-pound rail under the present Class " I " locomotive (Atlantic type) sometimes run as high as 22,000 pounds, while with the 80-pound rail stresses as high as 28,000 pounds are not uncommon. One thing, however, must be borne in mind: though the extreme fiber stress in steel rails may seem high as shown by test, these maximum stresses are of very short duration, lasting but a small fraction of a second and often reversed immediately. Within certain limits the stress seems to vary directly as a function of the speed; hence the greater the speed, the greater the stress, but the shorter its duration.

The present steel rails have an elastic limit between 50,000 pounds and 60,000 pounds and an ultimate strength of 110,000 pounds to 120,000 pounds as shown by test.

If we investigate the stresses which are supposed to exist under the Class " I " locomotives and then compare the resultant stresses with those of tests, we may arrive at a conclusion regarding the trustworthiness of our assumption.

As the Atlantic type of locomotive (Class " I ") cannot draw an ordinary train at a greater speed than 70 miles per hour with acceleration, we are justified in using 75 per cent impact in investigating the existing stresses under Class " I."

The Pacific type (Class " K ") and the electric locomotive (Class " T ") each may haul trains at speeds approaching 100 miles per hour,* and the former will be investigated with 100 per cent impact.

As the wheels roll along the rail there is a general depression of the track, local depressions being greater under the heaviest concentrations, and fairly uniform where the wheel loads are equal and evenly spaced. According to

* This statement seems open to question; compare with Article 3.

Dr. Dudley, this general depression varies from .10 inch to .20 inch, varying with the stiffness of the rail, elasticity of subgrade, and tamping of ballast. Due to the deflection of the rail, there will be a greater depression under the wheels and the lesser depression about midway between them. The tie pressure may be assumed proportional to the tie depression, and from the tie pressure the stress in the rail may be approximated.

In considering the deflection of the rail, we may consider the rail as a continuous beam being supported by the wheels and having varying concentrated loads applied by the ties. These concentrations decrease toward the center of the span and give an effect practically similar to that of the uniform load, equivalent to the sum of the tie pressure (Fig. 153).

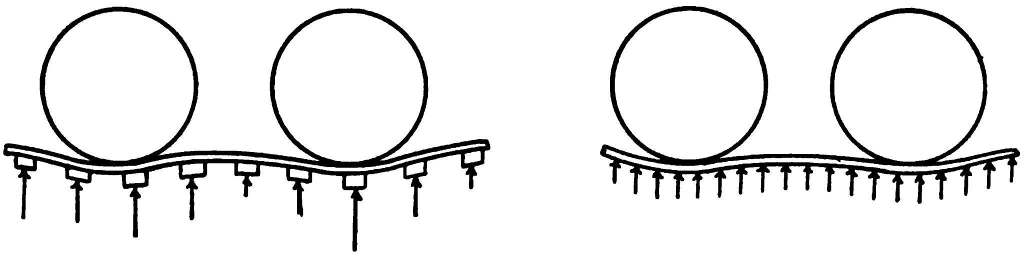


FIG. 153. — Distribution of Tie Pressure under Rail. (Freeman.)

In order to approximate the rail deflection, there will be no great error in considering the load of the drivers and second wheel of the first truck as uniformly distributed from a point between the two wheels of the forward truck to a point midway between the rear driver and the trailer; likewise that the load of the trailer be distributed from a point midway between the rear driver and the trailer to a point midway between the trailer and the first wheel of the tender.

The load of the drivers of the present Class "I" locomotive, including impact, is 96,000 pounds, which will be distributed over approximately 19 feet, giving an equivalent uniform load of 6400 pounds per lineal foot. Under the trailer the equivalent uniform load will be 4000 pounds per lineal foot, and under the front wheel about 3000 pounds per lineal foot (Fig. 154).

Under the drivers we have a span of 7 feet and a uniform load of 6400 pounds per lineal foot. With the 100-pound rail this loading would cause a deflection of .047 inch and with the 80-pound rail a deflection of .08 inch.

The average uniform load between the rear driver and the trailer being about 5000 pounds per lineal foot, the deflection of the 100-pound rail becomes .127 inch, while the 80-pound rail deflects .22 inch.

It will be seen by a glance at Fig. 155 that the tie reactions vary with the stiffness of the rail, being much more uniform with the heavier rail.

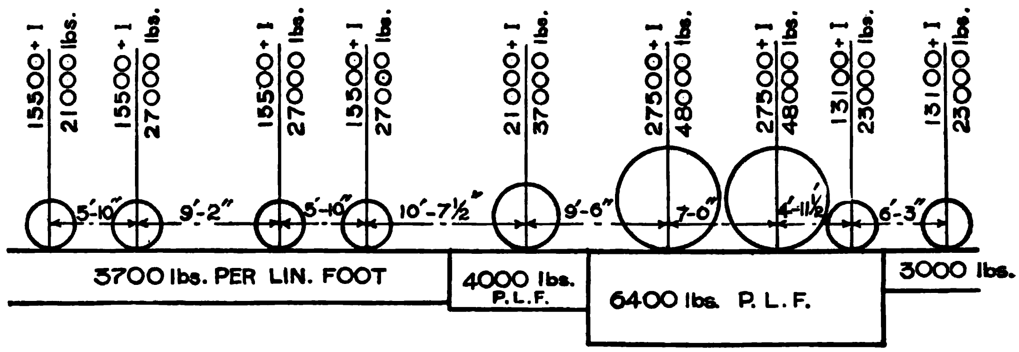


FIG. 154. — Class "I" Engine with 75 per cent Impact. (Freeman.)

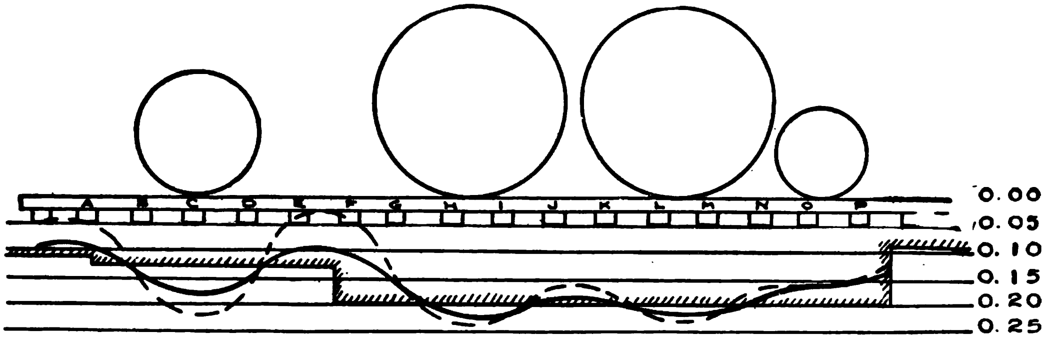


FIG. 155. — Track Depression under Class "I" Loading. (Freeman.)

Plotting the most probable deflection of the 100-pound rail (shown in solid line) and the 80-pound rail (shown in broken line), and then taking the tie reactions as proportional to the ordinates to the curves of deflection, we may expect the following depressions and reactions:

TABLE LI.—TIE DEPRESSIONS AND REACTIONS, CLASS "I" LOADING (FREEMAN)

Tie.	100-pound Rail.		80-pound Rail.	
	Depression.	Bearing.	Depression.	Bearing.
	Inch.	Pounds.	Inch.	Pounds.
A	0.10	5,300	0.04	2,200
B	0.15	8,100	0.18	10,000
C	0.19	10,200	0.23	12,600
D	0.15	8,100	0.18	10,000
E	0.10	5,300	0 04	2,200
F	0.10	5,300	0.04	2,200
G	0.17	9,400	0.17	9,500
H	0.22	11,800	0.2	13,400
I	0.22	11,800	0.24	13,400
J	0.18	9,700	0 17	9,500
K	0.18	9,700	0 17	9,500
L	0.22	11,800	0 24	13,400
M	0.22	11,800	0.24	13,400

If we use these tie reactions and assume with Winckler that the moments in a continuous girder over yielding supports are three-fourths those of a simple beam, we may compute the bending moments and the extreme fiber stress in the rail.

Taking moments under the rear driver, we find an extreme fiber stress of 19,430 pounds with the 100-pound rail and 28,950 pounds with the 80-pound rail. Under the trailer we find 17,750 pounds in the 100-pound rail and 19,800 pounds in the 80-pound rail.

These stresses given for Class "I" are practically those found from the stremmatograph tests.

According to Dr. Dudley, when the Class "I" type engine strikes a piece of soft or rough track, it begins pitching or rocking about its center of gravity, located between the two drivers. This rocking increases the pressure on the trailer sometimes as much as 50 per cent. This tends to increase the stresses under the trailer by that amount. In the Class "K" type, this difficulty is obviated to a great extent by the increased length of wheel base.

We may now compare Class "K" with Class "I," using 75 per cent impact and considering the two engines working under similar conditions.

Following the same analysis as in the investigation of Class "I," we may assume the weight of the drivers and the second wheel of the first truck as uniformly distributed over a length of about 28 feet of rail, giving a uniform load of 6500 pounds per lineal foot. Under the trailer we find a uniform load of 3800 pounds per lineal foot, and under the tender a load of 3700 pounds per lineal foot (Fig. 156).

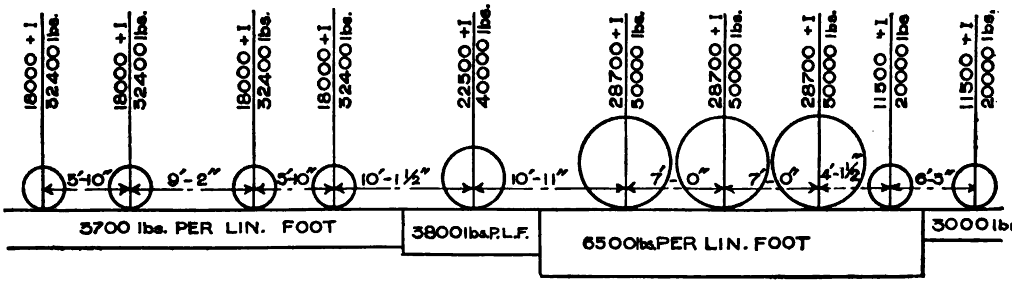


FIG. 156. — Class "K" Engine with 75 per cent Impact. (Freeman.)

Computing the deflections of the rail, we find .049 inch for the 100-pound rail and .083 inch for the 80-pound rail on the 7-foot span under the drivers; on the 10-foot 11-inch span between the rear driver and the trailer a deflection of .24 inch is shown by the 100-pound rail and .42 inch by the 80-pound rail.

Plotting the curve of probable deflections for the 100-pound and 80-pound rail and using a general average depression under the drivers, proportional to the uniform load under the drivers, we may find the tie depressions (Fig. 157).

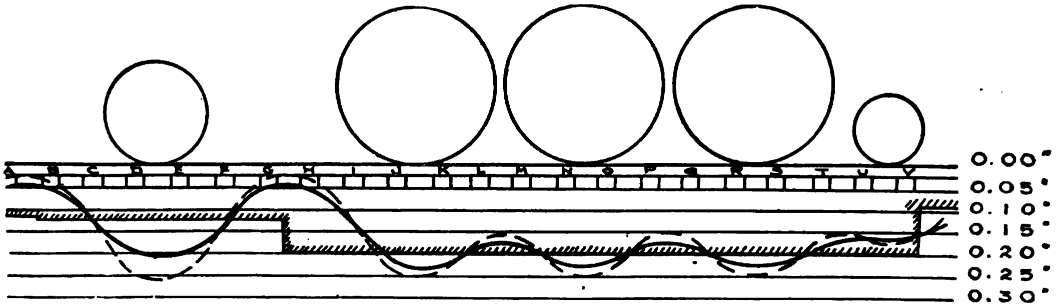


FIG. 157. — Track Depression under Class "K" Loading. (Freeman.)

The depression under a uniform load of 6500 pounds is taken at .20 inch. Upon this basis we get the following tie depressions and reactions:

TABLE LII.—TIE DEPRESSIONS AND REACTIONS, CLASS "K" LOADING (FREEMAN)

Tie.	100-pound Rail.			80-pound Rail.		
	Depression.	Bearing.		Depression.	Bearing.	
		I=75 Per cent.	I=100 Per cent.		I=75 Per cent.	I=100 Per cent.
A	0.05	3,000	3,400	0.03	1,560	1,780
B	0.05	3,000	3,400	0.03	1,560	1,780
C	0.14	7,000	8,000	0.11	5,700	6,500
D	0.20	10,000	11,400	0.25	13,000	14,850
E	0.20	10,000	11,400	0.25	13,000	14,850
F	0.14	7,000	8,000	0.13	6,800	7,800
G	0.05	3,000	3,400	0.03	1,100	1,260
H	0.05	3,100	3,500	0.04	1,300	1,500
I	0.13	7,900	9,000	0.14	9,100	10,400
J	0.23	14,000	16,000	0.24	15,600	17,800
K	0.23	14,000	16,000	0.24	15,600	17,800
L	0.18	11,000	12,600	0.16	10,400	11,900
M	0.18	11,000	12,600	0.16	10,400	11,900
N	0.23	14,000	16,000	0.24	15,600	17,800
O	0.23	14,000	16,000	0.24	15,600	17,800
P	0.18	11,000	12,600	0.16	10,400	11,900
Q	0.18	11,000	12,600	0.16	10,400	11,900

Taking moments under the rear driver, we find an extreme fiber stress of 22,000 pounds in the 100-pound rail and 32,150 pounds in the 80-pound rail. These stresses may be expected up to speeds of 60 miles per hour. At speeds of 90 to 100 miles per hour the impact will approach 100 per cent and the stress in the 100-pound rail may run as high as 25,200 pounds and up to 36,600 pounds in the 80-pound rail. These are stresses which may be expected in ordinary

main-line track, at maximum speed. On a soft piece of track they may run up 25 per cent higher.

Zimmerman's analysis of the stresses in the rail * is based upon the stiffness of the rail and tie and on the compressibility of the ballast. For the bending moment in the rail he derives the following equation:

$$M_0 = \frac{8\gamma + 7}{4\gamma + 10} G \frac{a}{4} = \frac{8\gamma + 7}{4\gamma + 10} m_0,$$

in which

M_0 = Maximum bending moment in the rail,

m_0 = Bending moment of a simple beam loaded in the middle of the span a with a load G,

G = Wheel load,

a = Distance center to center of ties,

$$\gamma = \frac{B}{D},$$

where

$$B = \frac{6EI}{a^3},$$

$$D = \frac{Cbl}{xz},$$

$$x = \sqrt[4]{\frac{Cb}{4EI}}.$$

E = Modulus of elasticity of the rail,

I = Moment of inertia of the rail,

b = The width of the tie,

l = One-half the length of the tie,

C = Coefficient of the ballast,

z = An auxiliary value depending on the form of the tie.

The coefficient of ballast represents the pressure in kilograms per square centimeter of the ballast which causes a depression of one centimeter. The coefficient 3 corresponds with simple gravel and the coefficient 8 with gravel on a bed of dry stone or on rocky soil.

Fig. 158 shows that the ratio $\frac{M_0}{m_0}$ increases with γ, that is to say, with the stiffness of the rail and the flexibility of the tie.

Table LIII presents calculations for several German railroads by the aid of Zimmerman's formulæ. The table is taken from an article on "The Track Superstructure of German Railways" by M. Blum in the Revue Générale

* Calculation of the Superstructure, Berlin, 1888.

des Chemins de Fer, No. 5, November, 1908, a translation of which is given in Proceedings American Railway Engineering and Maintenance of Way Association, Vol. 11, Part 2, 1910.

Fig. 158. — Bending Moment of Rail placed on Ties. (Zimmerman.)

In questions of such moment we cannot rely on mathematical analyses for conclusions. We can deduce general results from specific experiments by their aid, but it is somewhat unsafe to attempt any generalization on its evidence alone.

22. Tests to Determine the Bending Stress in the Rail

* Experiments were made in the track of the Boston and Albany Railroad in 1889. The experiments consist in measuring the depression of the rail at different places along the length when loaded, and in measuring the extension or compression of the metal at the upper surface of the base of the rail, near the edge of the outside flange.

For measuring the depression a row of stakes was driven alongside the track, three feet away, and the relative level of points on the base of the rail and nails in the tops of the stakes was ascertained by means of a sensitive spirit level.

For ascertaining the strains, gauged lengths of 5 inches each were established and defined by center punch marks on the base of the rail at places over the ties and midway between them, and the amount of extension or compression, as the case might be, was measured on these gauged lengths.

The rails were 72 pounds per yard, $4\frac{1}{2}$ inches high and $4\frac{1}{2}$ inches width of base. The results of the experiments are shown in Fig. 159.

* House Executive Documents, 1st Session, 51st Congress, 1889–90, Vol. 25, Tests on Metals.

NSEIGHTS, A

		13
ngle.		
Per		Ratio, $\frac{f}{e}$
os.		
).6	16	1.23
7.5	3	1.23
11.9		1.12
91.5		1.12
90.0		1.31
80.0		1.11
......		1.82
49.1		.47
66.0		35
75.5		.4
101.0		3

OTE.—C27 are

* Experiments were made by the Ordnance Department, U. S. Army, during the month of October, 1893, on the track of the Chicago, Burlington and Quincy Railroad, at Hawthorne, Ill.

The experiments consisted of measuring the depression of the rails under the weights of different classes of locomotives, and the fiber stresses developed in the base of the rail.

For the purpose of observing the depression of the rails, bench marks were established on a row of stakes driven alongside the rail, 31 inches distant from

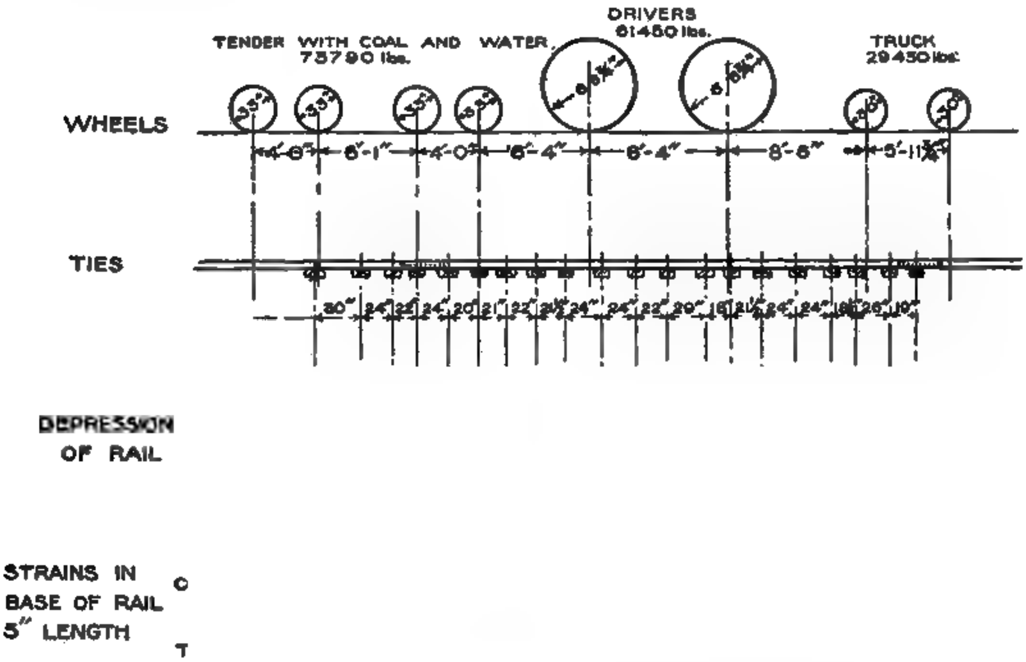


Fig. 159. — Railroad Track Experiments, Boston and Albany R. R.

it. A beam carrying a micrometer and an astronomical level bubble were used in observing the depression of the rail (see Fig. 160), first measuring the height, using points on the outer flange, when the rail was unloaded, and repeating the observations when the engine was standing on the track.

It was found that the roadbed in the vicinity of the locomotives was sensibly depressed and that the bench marks were within the influence of that depression. It was possible to detect a depression of the roadbed as far as 91 inches from the locomotive at the side of the track.

A correction for the depression of the bench marks was obtained by means of a cantilever supported 10 feet from the track, and the total depression of

* House Executive Documents, 3rd Session, 53rd Congress, 1894–95, Vol. 30, Tests of Metals, etc.

FIG. 160. — Railroad Track Experiments.
Photograph of Leveling Instrument for Measuring the Depression of the Track.

FIG. 161. — Railroad Track Experiments.
Photograph of Micrometer for Determining the Fibre Stress in the Base of the Rail.

points on the rails was also determined with reference to the cantilevers in some of the experiments instead of using stakes.

The fiber stresses were determined in the base of the rail by measuring the elongation or compression of the metal on a gauged length of 5 inches, established on the top surface of the outer flange, observing the strains when the wheels were directly over or when spanning the gauged length (see Fig. 161).

The observed strains were then computed for the stresses per square inch, assuming a modulus of elasticity of 30,000,000 pounds per square inch and that the fibers in the base were strained proportionally to their distance from the neutral axis of the rail; the computed stresses referring to the outside fibers most remote from the neutral axis.

It will be observed that the strains and the computed stresses refer to a gauged length of 5 inches, and, consequently, the maximum stresses may be somewhat greater than those shown, considering the maximum bending moment to be directly under the point of application of the load. Some of the results are graphically shown in Fig. 162.

The moment of inertia of the 66-pound rail tested was 19.127 and the section modulus of the base $\frac{19.127}{2.24} = 8.54$.

Fig. 162A shows the depression of one rail its entire length and the ends of contiguous rails, the locomotive occupying one position thereon as shown with reference to the rail and ties.

Fig. 162B shows the curve of depression under another type of locomotive. This engine had no leading truck nor tender, but had a two-wheeled trailing truck.

In the position it occupied during the test, the greatest depression of the rail occurred under the forward drivers, the rail presenting a sharp acclivity before the engine, and beyond the joint the contiguous rail rose slightly above the normal level.

In the diagram, Fig. 162C, are shown the fiber stresses as measured on the base of the rail at station $14\frac{1}{2}$, midway between ties Nos. 14 and 15.

Advance wave determinations were made on the 66-pound rail on cinder ballast (8 inches under the tie) with the same class engine as shown in Fig. 162A, the engine weighing 125,000 pounds. With the locomotive slowly approaching, an upward movement of the rail began when the leading truck wheel was about 15 feet away; the wave increased while the locomotive continued to advance, reaching a maximum of .0037 inch when the truck wheel was about $8\frac{1}{2}$ feet away. Then followed a sudden depression, and the height of the rail was reduced to the normal level when the truck wheel was about $7\frac{1}{2}$ feet away.

The position of the locomotive when the upward motion of the wave first reached the station could be identified with considerable precision, but, owing to an appreciable interval of time being necessary for the level bubble of the

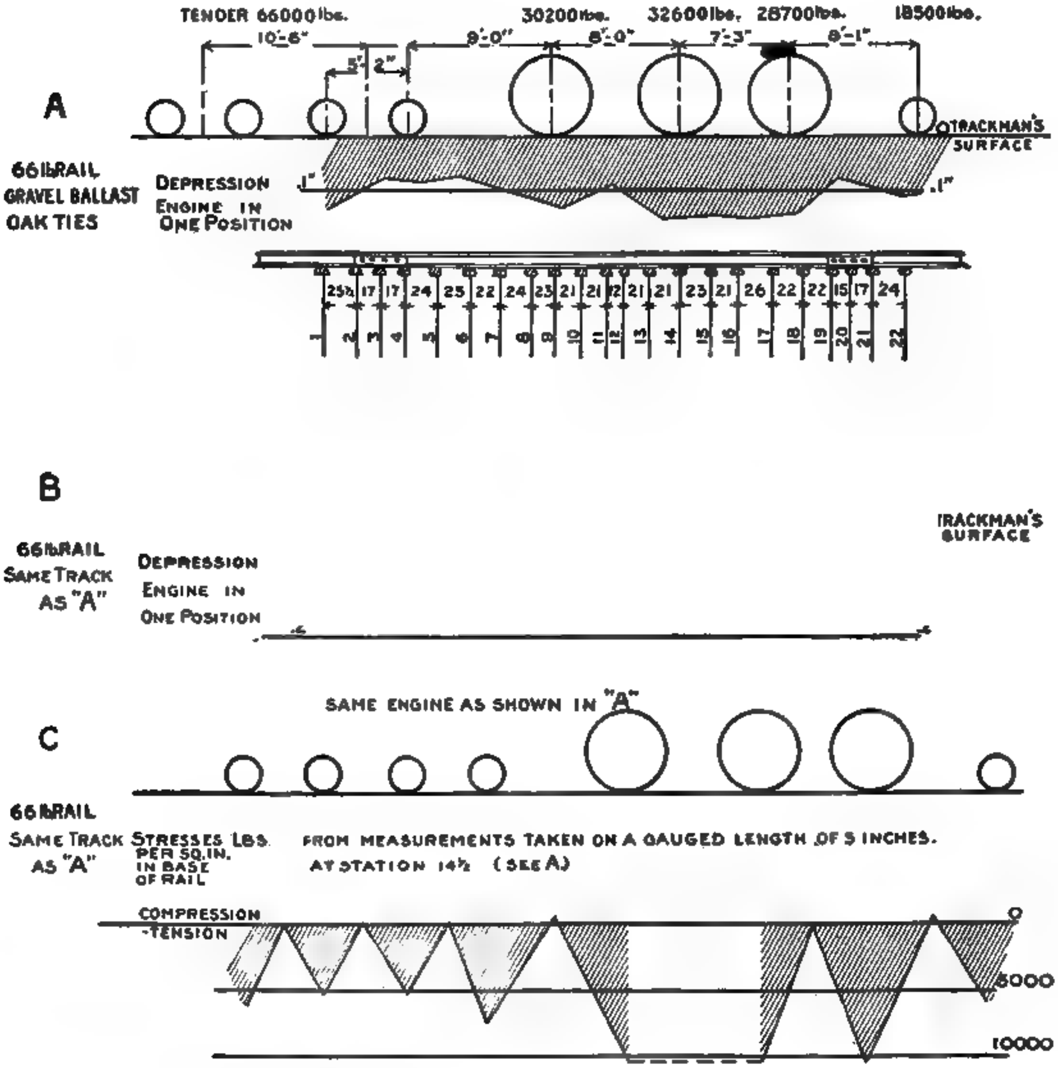


FIG. 162. — Railroad Track Experiments. C. B. & Q. R. R.

measuring instrument to stop and reverse the direction of its movement, the position of the crest of the wave, as well as the time when the height of the rail was returned to its normal level, could not be so well defined.

The wave length was probably somewhat less than the observations showed. The abruptness with which the direction of the wave motion was changed and

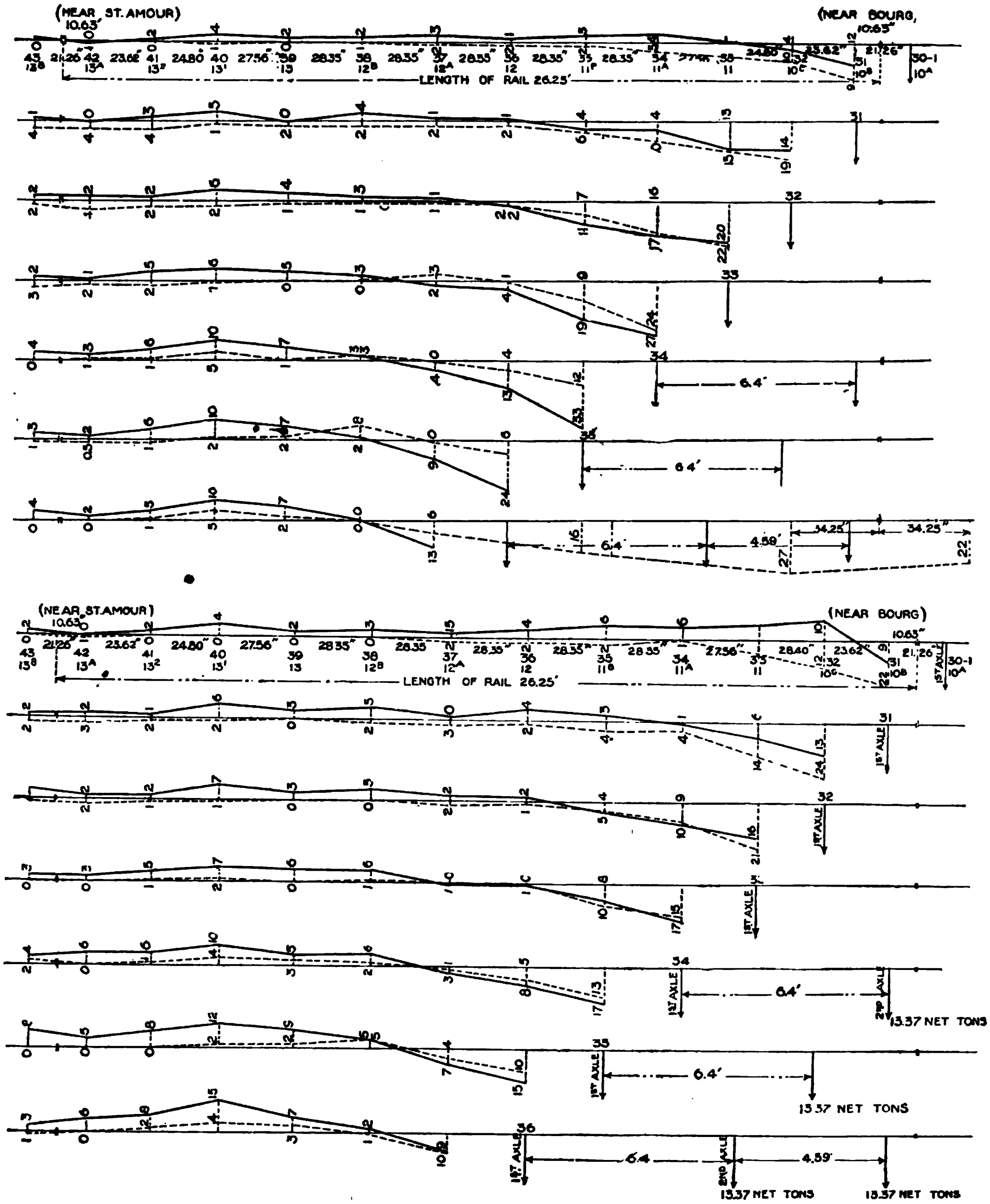


FIG. 163. — Advance Wave Determinations. (Cuënot.)

the rail returned to its normal level, after which, of course, it was depressed below the normal, was a very striking feature of the observations.*

* Fig. 163 shows the advance wave observed by M. Cuënot. It was found that when the first wheel of the engine is about 20 feet from a tie the upward movement commences and reaches a maximum at about 10 feet.

The observations of the depression of the roadbed made in these experiments are of importance. On cinder ballast that part of the roadbed in which the stakes were driven (31 inches from the track) was depressed a maximum of .049 inch and on gravel ballast the maximum was .036 inch. Wooden stakes and iron bolts were driven different depths into the roadbed with similar results; in fact, the few observations which were made showed the longer stakes to have been quite as much depressed as the shorter ones, which did not penetrate the cinder ballast.

Following out the depression of the roadbed in a lateral direction, on cinder ballast, when the middle driver of the engine was abreast the place of observation, there was a measurable depression at a distance of 91 inches from the rail.

Fig. 164. — Movement of Rails Laid Alongside of Track.

The right-hand rail lying by the near telegraph pole moved 40 feet. The trail it left may be traced from a point near the angle bar in the foreground. (Railroad Age Gazette, Dec. 17, 1909.)

The recovery in the depression of the roadbed was not complete immediately upon the removal of the engine from that vicinity. The principal part of the recovery at once took place; the remaining portion of the depression, however, was very sluggish in returning. The length of time required to effect complete resilience was not determined. One observation, however, made nine minutes after the load was removed from the vicinity, showed the resilience then incomplete.

Fig. 164 shows an exaggerated case of the wave motion and depression of the track. The road runs on an embankment about five feet above the level of a wet meadow. The wave motion of the track and embankment is so great that rails lying by the side of the track move along apparently of their own accord at the rate of nearly a foot a day. This movement was undoubtedly due to the undulatory movement of the track and entire fill and probably some reaction of the fill itself against the track.

Further tests were made in 1894 and 1895 on the tracks of the Pennsylvania Railroad and the Boston and Albany by the Government. * These experiments comprise observations on the fiber stresses developed in rails in the track, the depression of the rails, and the slope or inclination of the rails caused by the weight of the different wheels of the locomotive. The results show some phenomena displayed by rails in service under the static conditions of loading or when a locomotive passes slowly over the track.

The series were made chiefly on the track of the Pennsylvania Railroad, where exceptional opportunities existed for examining roadbed, embracing a wide variety of conditions of weight of rails and different kinds of ballast and its behavior under heavy types of freight and passenger locomotives.

The tests were made during the early part of the month of November, 1894, on track in the condition it was found in service.

The experiments on the Boston and Albany Railroad were made with track on frozen gravel ballast, in the month of February, 1895.

The fiber stress tests were made by means of a micrometer mounted on the upper side of the flange of the base of the rail, at a place midway adjacent ties. The instrument covered a gauged length of 5 inches. The micrometer was adjusted in position, and then the several wheels of the locomotive were successively brought over the gauged length, or until the same was midway adjacent wheels.

The instrument was read when the locomotive was at each of these positions. It was found practicable to make the micrometer observations without arresting the locomotive in all cases, taking the readings as the locomotive passed slowly over the rail. In this manner the strains developed were measured, an elongation of the metal showing tensile stress, and a contraction in the gauged length showing compressive stress.

The measured strains were reduced to stresses per square inch, assuming the modulus of elasticity of the steel to be 30,000,000 pounds per square inch, and correcting the observed strains in order to obtain the maximum fiber stresses,

* House Documents, Vol. 46, 54th Congress, 1st Session, 1895–96. No. 54, Tests of Metals.

on the further assumption that the strains were proportional to their distance from the neutral axis of the rail.

Fig. 165 shows the micrometer in position on the base of the rail, under the driving wheel of a locomotive.

The depression of the rails was measured by means of a sensitive level bubble, mounted on a rod, carrying at one end a screw micrometer, which

FIG. 165.—Railroad Track Experiments.

View showing Micrometer for Measuring Strains in Rails, in Position on Base of Rail under Driving Wheel.

rested on a stake driven in the roadbed 30 inches from the rail; the other end of the rod rested upon the base of the rail. The depression of the track was thus measured with reference to the top of the stake used as a bench mark. In this series it was necessary to arrest the movement of the locomotive at each observation.

The slope tests, or inclination of the rails, were made by means of a sensitive level bubble mounted on a frame 12 inches long. At one end of the frame there

was a fixed supporting rod having a conical point; at the other end there was a screw micrometer, the contact end of which was also made with a conical point.

In the use of this instrument, two center punch marks, 12 inches apart, were made on the base of the rail. The conical points of the instrument entered these center punch marks and furnished definite contact points with the rail. The instrument was then leveled and the changes in slope, when the rail was affected by the locomotive, were measured from this initial adjustment of the level bubble.

Fig. 165 shows the slope instrument resting on the second tie to the right of the fiber-stress micrometer. The rails examined ranged in weight from 60 to 100 pounds per yard, and were supported on oak ties resting on cinder, gravel, and stone ballast, in the case of the Pennsylvania Railroad.

On the Boston and Albany Railroad, yellow pine ties, with shoulder tie plates, were used, the roadbed being ballasted with gravel, which was in a frozen condition at the time of the tests.

TABLE LIV. — RAILROAD TRACK EXPERIMENTS. GENERAL DIMENSIONS OF RAILS

GOVERNMENT RAIL TESTS

(House Documents, Vol. 46, 54th Congress, 1st Session, 1895–96. No. 54, Tests of Metals)

Weight per Yard.	Height.	Width of Base.	Width of Head.	Thickness of Web.	Moment of Inertia.	Moment of Resistance.	Distance, Neutral Axis to Outside Fiber.	
Pounds.	Inches.	Inches.	Inches.	Inch.	I	$R = \frac{I}{n'}$.	Head n Inches.	Base n' Inches.
60	$4\frac{1}{4}$	$4\frac{1}{4}$	$2\frac{3}{8}$	$\frac{1}{2}$	14.222	6.693	2.125	2.125
70	$4\frac{1}{2}$	$4\frac{1}{2}$	$2\frac{7}{16}$	$\frac{1}{2}$	18.055	8.282	2.32	2.18
85	5	5	$2\frac{9}{16}$	$\frac{17}{32}$	26.374	10.853	2.57	2.43
100	$5\frac{1}{2}$	$5\frac{1}{2}$	$2\frac{13}{16}$	$\frac{5}{8}$	38.957	14.812	2.87	2.63
95	$5\frac{1}{32}$	$5\frac{1}{2}$	3	$\frac{5}{8}$	32.28	13.563	2.65	2.38

The general dimensions of the rails are given in Table LIV. What was then considered a heavy type of freight and passenger locomotive was employed, the weights of which are recorded in Table LV.

Referring to the tests on the Pennsylvania Railroad, the tensile fiber stresses developed under the weight of the driving wheels ranged from 2810 to 19,540 pounds per square inch, and the compression stresses, when the gauged length was between wheels, reached 7880 pounds per square inch. These values belonged to the rails in their ordinary condition of service. A tie was removed from the track, laid with 100-pound rail, which increased the distance between centers of ties to 52 inches, and here the maximum tensile stress developed was 18,970 pounds per square inch, against 9840 pounds per square inch for another rail of the same section resting on ties 26 inches apart.

A splice bar on a 70-pound rail was strained 22,140 pounds per square inch, tension, and 8300 pounds per square inch, compression stress, by the driver of passenger engine No. 809.

TABLE LV. — WEIGHTS OF LOCOMOTIVES

GOVERNMENT RAIL TESTS

(House Documents, Vol. 46, 54th Congress, 1st Session, 1895-96. No. 54, Tests of Metals)

Locomotive.	Total.	Engine.		Tender.	Weight per Wheel.		
		Pilot.	Drivers.		Wheel.	Pounds.	Tons.
	Pounds.	Pounds.	Pounds.	Pounds.			
Passenger No. 809, Class PK.	197 050	39,750	87,300	70,000	Pilot..........	9,937	4.968
					Driver, first...	21,750	10.875
					Driver, second.	21,900	10.950
					Tender........	8,750	4.375
Passenger No. 1515, Class T.	222,500	50,300	95,200	77,000	Pilot..........	12,575	6.287
					Driver, first...	24,250	12.125
					Driver, second.	23,350	11.675
					Tender........	12,833	6.416
Freight No. 557, Class R.	188,600	11,000	800	63,800	Pilot..........	5,500	2.750
					Driver, first...	13,250	6.625
					Driver, second.	13,750	6.875
					Driver, third..	15,650	7.825
					Driver, fourth..	14,250	7.125
					Tender........	7,975	3.987
Passenger No. 209, B. & A. R.R.	199,700	40,700	75,000	84,000	Pilot..........	10,175	5.087
					Driver, first...	18,750	9.375
					Driver, second.	18,750	9.375
					Tender.......	....	....
					First truck....	9,250	4.625
					Second truck...	11,750	5.875

Table LVI shows the maximum tensile fiber stress caused by the wheels of the pilot, engine, and tender on the different rails and kinds of ballast, also the maximum compression stresses developed in each experiment. The place of observation in these experiments was between ties and about one-quarter of the length of the rail from the end.

From the irregular manner in which the stresses were developed in the different weights of rail, it is evident that the peculiar condition of the track at individual rails has an important influence on the magnitude of the fiber stresses.

The lightest section of rail examined, 60 pounds per yard, resting on ties on gravel ballast, gave exceptionally low fiber stresses, and it will be seen that this rail was depressed a correspondingly small amount.

So much variation is found in the stresses as to practically obscure the relative strength of the different weights of rails, and it seems necessary to compare the extreme sections to show a well-defined difference in the maximum stresses.

On account of the peculiar conditions influencing the behavior of the individual rails, the relative values of the different kinds of ballast are less conspicuously shown in the fiber-stress experiments than in the series on the depression of the rails.

TABLE LVI.—MAXIMUM FIBER STRESSES IN BASE OF RAIL

GOVERNMENT RAIL TESTS

(House Documents, Vol. 46, 54th Congress, 1st Session, 1895-96. No. 54, Tests of Metals)

Rail Weight per Yard.	Ballast.	Locomotive.	Tensile Fiber Stress per Square Inch. (Pounds.)			Compressive Fiber Stress per Square Inch.
			Pilot.	Drivers.	Tender.	
Pounds.						Pounds.
60	Gravel	Passenger No. 809	6,180	11,670	2,750	1,370
60	Gravel	Freight No. 557	3,430	7,550	3,430	690
60	Stone	Passenger No. 809	11,860	19,540	9,770	3,490
60	Stone	Freight No. 557	11,160	16,050	9,770	1,400
70	Cinder	Passenger No. 809	10,730	17,170	10,020	4,290
70	Gravel	Passenger No. 809	8,970	18,620	8,280	5,520
70	Gravel	Freight No. 557	7,590	13,790	6,210	4,830
70	Stone	Passenger No. 809	10,070	14,390	7,910	6,470
70	Stone	Freight No. 557	6,470	11,510	6,470	2,880
70	Bridge	Passenger No. 809	9,450	18,180	10,910	2,180
70	Splice bar	Passenger No. 809	13,840	22,140	9,230	8,300
85	Cinder	Passenger No. 809	7,160	10,030	5,020	3,580
85	Cinder	Passenger No. 1515	5,730	12,180	7,880	4,300
85	Cinder	Freight No. 557	3,580	10,030	5,020	4,300
85	Gravel	Passenger No. 809	10,750	12,180	6,450	4,300
85	Gravel	Passenger No. 1515	9,310	17,120	9,310	5,020
85	Gravel	Freight No. 557	7,160	10,030	2,870	7,880
85	Stone	Passenger No. 809	7,160	10,750	4,300	4,300
85	Stone	Freight No. 557	4,300	10,030	5,020	3,580
100	Stone	Passenger No. 809	6,320	9,840	5,620	4,220
100	Stone, tie removed	Passenger No. 809	10,540	18,970	8,430	2,110
100	Stone	Freight No. 557	3,510	8,430	4,220	2,810
95	Frozen gravel, rail No. 1	Passenger No. 209	6,870	9,920	6,870	3,050
95	Frozen gravel, rail No. 2	Passenger No. 209	7,630	11,450	6,870	*7,630

* Taken at different points on the rail.

The relative effect of the several wheels of the locomotives are shown with greater precision than some other features of the test, inasmuch as in this comparison the action of all wheels are referred to the same point on the rail. Table LVII shows the tensile stresses developed per ton weight on the different wheels of each locomotive on the several rails. From these results it appears that the stresses are generally greatest under the outside wheels.

An examination of the results shows, as an extreme case, that the pilot wheels of freight engine No. 557 on a 60-pound rail, with stone ballast, gave a fiber stress of 4058 pounds per square inch per ton on the wheel, whereas the first driver of the engine, per ton, strained the rail only 1685 pounds per square inch. In this instance the total stress per square inch was the same under these two wheels, namely, 11,160 pounds, although the weight on the drivers was more than twice that on the pilot wheel.

TABLE LVII.—TENSILE FIBER STRESSES IN BASES OF RAILS PER TON WEIGHT ON THE DIFFERENT WHEELS

GOVERNMENT RAIL TESTS

(House Documents, Vol. 46, 54th Congress, 1st Session, 1895-96. No. 54, Tests of Metals)

PASSENGER LOCOMOTIVES

Rail Weight per Yard.	Locomotive.	Ballast.	Tensile Fiber Stress (in Pounds) per Ton Weight on Wheels of							
			Pilot.		Driver.		Tender.			
			1	2	1	2	1	2	3	4
Pounds.										
70	No. 809	Cinder	2160	2017	1578	1568	1799	1799	1634	2290
85	No. 809	Cinder	1440	721	949	916	1147	656	656	983
85	No. 1515	Cinder	911	911	945	1043	1228	782	1116	......
60	No. 809	Gravel	1244	829	1073	949	471	629	629	629
70	No. 809	Gravel	1805	1805	1585	1700	1262	1735	1262	1893
85	No. 809	Gravel	2164	866	1054	1112	1474	1474	1147	1474
85	No. 1515	Gravel	1481	911	1359	1466	893	1116	1451	......
60	No. 809	Stone	2387	2387	1798	1784	1595	1913	1595	2279
70	No. 809	Stone	2027	1157	1323	1314	1152	1152	1152	1808
85	No. 809	Stone	1441	866	989	785	983	818	818	983
100	No. 809	Stone	1272	566	905	899	642	642	642	1285
100	No. 809	Stone, tie removed	2122	1415	1422	1732	1607	1607	1285	1927
70	No. 809	Bridge	1463	1902	1672	1328	2327	1995	1995	2494
70	No. 809	Splice bar	2786	2228	1697	2022	1897	1477	1687	2110
95 D	No. 209	Frozen gravel, rail No. 1	1199	900	733	977	659	973	909	1169
95 L	No. 209	Frozen gravel, rail No. 1	1351	1050	977	1058	826	826	1038	1169
95 B	No. 209	Frozen gravel, rail No. 2	1500	1351	1139	1221	990	1485	909	909
95 D	No. 209	Frozen gravel, rail No. 2	1351	1050	1025	1221	1319	1485	1038	1038
95 H	No. 209	Frozen gravel, rail No. 2	1500	1050	814	1139	1155	1155	909	1038
95 K	No. 209	Frozen gravel, rail No. 2	1500	1050	895	1025	1155	1155	1169	1038
95 L	No. 209	Frozen gravel, rail No. 2	900	301	489	570	331	0	0	519
95 M	No. 209	Frozen gravel, rail No. 2	1050	149	408	651	331	−164	129	260
95 N	No. 209	Frozen gravel, rail No. 2	751	600	651	733	659	495	519	650

FREIGHT LOCOMOTIVES

Rail Weight per Yard.	Locomotive.	Ballast.	Tensile Fiber Stress (in Pounds) per Ton Weight on Wheels of								
			Pilot.	Drivers.				Tender.			
				1	2	3	4	1	2	3	4
Pounds.											
85	No. 557	Cinder	1302	540	1041	366	1408	898	898	720	1259
60	No. 557	Gravel	1247	518	999	878	1060	860	617	860	860
70	No. 557	Gravel	2760	1250	1805	1323	2512	1558	1384	1038	1384
85	No. 557	Gravel	2604	974	1146	824	1408	720	720	359	720
60	No. 557	Stone	4058	1685	2335	1872	2056	2450	1926	2275	2450
70	No. 557	Stone	2353	761	1046	1011	1615	1264	1084	903	1623
85	No. 557	Stone	1564	865	1041	732	1408	1078	898	898	1259
100	No. 557	Stone	1276	424	511	718	1183	705	880	351	1058

Throughout this and earlier series of track experiments the same tendency has been found, the outside wheels exerting the most severe action on the rails in proportion to the weight which they carry.

The maximum and minimum tensile stresses per ton on the different wheels are shown in Table LVIII.

TABLE LVIII. — MAXIMUM AND MINIMUM TENSILE STRESSES PER TON ON THE DIFFERENT WHEELS

GOVERNMENT RAIL TESTS

(House Documents, Vol. 46, 54th Congress, 1st Session, 1895-96. No. 54, Tests of Metals)

Rail Weight per Yard.	Ballast.	Locomotive.	Maximum Stress.		Minimum Stress.	
			Wheel.	Per Square Inch.	Wheel.	Per Square Inch.
Pounds.				Pounds.		Pounds.
60	Gravel...........	Passenger No. 809..	1st pilot...	1244	1st tender....	471
60	Gravel...........	Freight No. 557....	Pilot......	1247	1st driver....	518
60	Stone............	Passenger No. 809..	Pilot......	2387	3rd tender...	1595
60	Stone............	Freight No. 557....	Pilot......	4058	1st driver....	1685
70	Cinder...........	Passenger No. 809..	4th tender..	2290	2nd driver...	1568
70	Gravel...........	Passenger No. 809..	4th tender..	1893	1st tender...	1262
70	Gravel...........	Freight No. 557....	Pilot.......	2760	3rd tender...	1038
70	Stone............	Passenger No. 809..	1st pilot....	2027	1st, 2nd, 3rd tender	1152
70	Stone............	Freight No. 557....	Pilot.......	2353	1st driver....	761
70	Bridge...........	Passenger No. 809..	4th tender.	2494	2nd driver ..	1328
70	Splice bar........	Passenger No. 809..	1st pilot....	2789	2nd tender...	1477
85	Cinder......... ...	Passenger No. 809..	1st pilot....	1441	2nd, 3rd tender	654
85	Cinder...........	Passenger No. 1515.	1st tender...	1228	2nd pilot....	782
85	Cinder...........	Freight No. 557....	4th driver...	1408	1st driver....	540
85	Gravel...........	Passenger No. 809..	1st pilot....	2164	2nd pilot.....	866
85	Gravel...........	Passenger No. 1515.	1st pilot...	1481	1st tender...	893
85	Gravel...........	Freight No. 557....	Pilot.......	2604	3rd tender...	359
85	Stone............	Passenger No. 809..	1st pilot....	1441	2nd, 3rd tender	818
85	Stone............	Freight No. 557....	Pilot......	1564	3rd driver...	732
100	Stone............	Passenger No. 809..	1st pilot...	1272	2nd pilot.....	566
100	Stone, tie removed	Passenger No. 809..	1st pilot...	2122	3rd driver...	1285
100	Stone............	Freight No. 557....	Pilot......	1276	3rd driver...	451
95	Gravel, frozen* ...	Passenger No. 209..	1st pilot....	1199	1st driver....	733
95	Gravel, frozen* ...	Passenger No. 209..	1st pilot....	1351	1st tender...	826
95	Gravel, frozen† ...	Passenger No. 209..	1st pilot....	1500	3rd, 4th tender	909
95	Gravel, frozen† ...	Passenger No. 209..	2nd tender..	1485	1st driver....	1025
95	Gravel, frozen† ...	Passenger No. 209..	1st pilot....	1500	1st driver....	814
95	Gravel, frozen† ...	Passenger No. 209..	1st pilot....	1500	1st driver....	895
95	Gravel, frozen† ...	Passenger No. 209..	1st pilot....	900	2nd, 3rd tender	0
95	Gravel, frozen† ...	Passenger No. 209..	1st pilot....	1050	2nd tender...	−164
95	Gravel, frozen† ...	Passenger No. 209..	1st pilot....	751	2nd tender...	495

* Rail No. 1. † Rail No. 2.

Illustrative of the influence which the condition of the roadbed has on the fiber stresses, the 60-pound rail on gravel ballast showed 1247 pounds per square inch stress per ton under the pilot wheel of the engine, whereas,

with the same weight of rail on stone ballast, the same wheel gave 4058 pounds per square inch.

The fiber stress experiments on the Boston and Albany Railroad were made on rails 95 pounds per yard, on frozen gravel ballast, and observations were taken at several points along the length of the rails. The observations on rail No. 1 were made with the rail in the condition in which it was found in the track. There was some looseness between the tie plates and the rail and ties, which, in rail No. 2, was diminished as far as possible by redriving the spikes and by the use of a number of additional ones. This is the only instance in which spikes were redriven before testing. Rail No. 1 was examined at two, and No. 2 was examined at seven, places along its length.

The tensile fiber stresses at the first end of rail No. 2 were higher than those developed at the middle and near the second end of the rail. In this rail, as the tensile stresses diminished at the second end, the compressive stresses increased. At a space 33 inches from the end of the rail, the compressive stress in the base reached 7630 pounds per square inch when this space was midway the drivers. The same stress was also shown when the space was between the tender trucks.

Concerning the relation between the fiber stress developed and the total depression of the rail, the evidence generally favors the deduction that diminished depression will be accompanied by diminished fiber stress.

The depression of the rails examined on the Pennsylvania Railroad shows, with the 60-pound rails, the least depression on the gravel ballast, the order of rigidity being gravel, stone, and cinder ballast. With the 70-pound sections, the order of rigidity is gravel, cinder, and stone ballast. Under the 85-pound rails, the stone ballast gave greater rigidity than the gravel. No test for depression was made with cinder ballast under the 85-pound rails, and only stone ballast was used under the 100-pound rails.

Table LIX states the mean depression of the driving wheels, and also the mean depression of all the other wheels of the locomotive in each experiment. There is in the table a column of differences which states the excess of depression of the drivers over that of the other wheels. The column of differences is useful in showing the additional depression of the rails under the weights of the driving wheels after they have been loaded by the other wheels.

Under the 60- and 70-pound sections, the gravel ballast gave the greatest rigidity under the drivers, as well as under the other wheels, and in the column of differences the excess of depression was least for this kind of ballast.

The total depression with 85-pound rails was less for the stone than for the gravel ballast, although the excess of depression under the drivers was practically the same in the two cases.

The depression of the rails on frozen gravel ballast, in which there was no visible movement of the ties, would seem to represent about the attainable limit of rigidity in track on wooden ties.

The fact that 60-pound rail on gravel compares favorably with the heavier section on the frozen ballast indicates that this light section of rail was in a condition approaching rigidity.

In the slope tests, the approach of the locomotive was felt for a distance of 12 to 15 feet in front of the first wheel. The first observed movement was

TABLE LIX.—DEPRESSION OF RAILS—MEAN DEPRESSION UNDER DRIVING WHEELS AND MEAN DEPRESSION UNDER PILOT AND TENDER WHEELS

GOVERNMENT RAIL TESTS

(House Documents, Vol. 46, 54th Congress, 1st Sess'on, 1805–96. No. 54, Tests of Metals)

Rail Weight per Yard.	Ballast.	Locomotive.	Drivers.	Pilot and Tender.	Difference.
Pounds.			Inch.	Inch.	Inch.
60	Cinder	Passenger No. 809	.229	.154	.075
60	Gravel	Passenger No. 809	.073	.042	.031
60	Stone	Passenger No. 809	.162	.122	.040
70	Cinder	Passenger No. 809	.230	.157	.073
70	Gravel	Passenger No. 809	.138	.089	.049
70	Stone	Passenger No. 809	.277	.207	.070
85	Gravel	Passenger No. 809	.233	.184	.049
85	Stone	Passenger No. 809	.144	.097	.047
100	Stone	Passenger No. 809	.168	.116	.052
95	Gravel, frozen, rail No. 1	Passenger No. 209	.139	.103	.036

an upward one, the inclination of the rail sloping in a direction from the locomotive. This was followed by a reversal in the direction of the inclination, which then sloped toward the locomotive. As the several wheels successively passed over the place of observation, the inclination of the slope reached a maximum and was reversed in direction, these motions being repeated under each wheel with some modifications, according to the condition of the track. After the locomotive had passed over the place of observation the inclination gradually diminished, and eventually the rail practically resumed its original level. A very critical examination led to the conclusion that each passage of a locomotive left the rail in a slightly different state than it before occupied, and that some sluggishness of recovery in the ballast had an influence on these minute displacements.

Figs. 166 and 167 show graphically the results of the tests for depression and stress in different kinds of ballast and weights of rails.

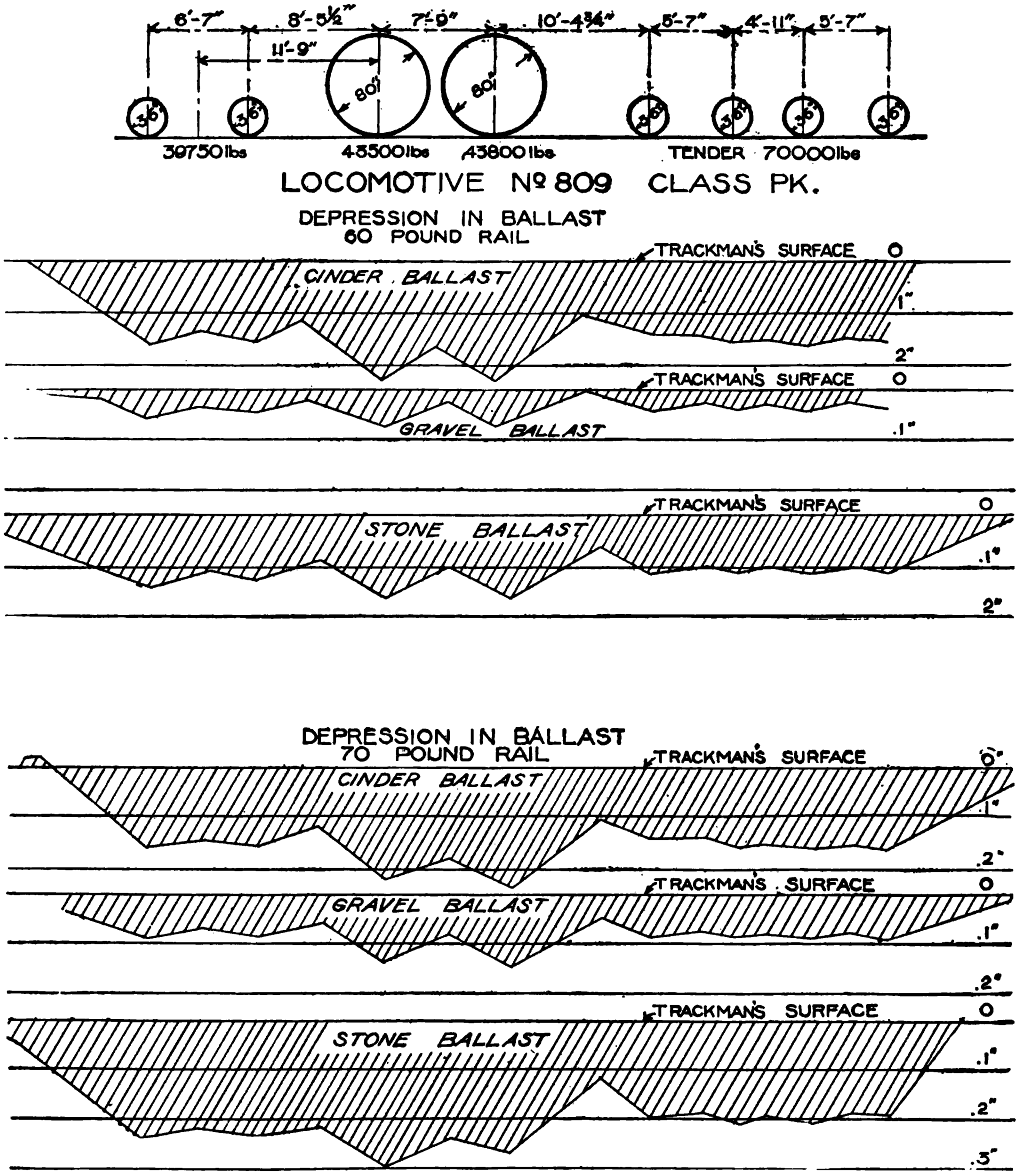


FIG. 166. — Railroad Track Experiments, Pennsylvania R. R. Depression in Ballast.

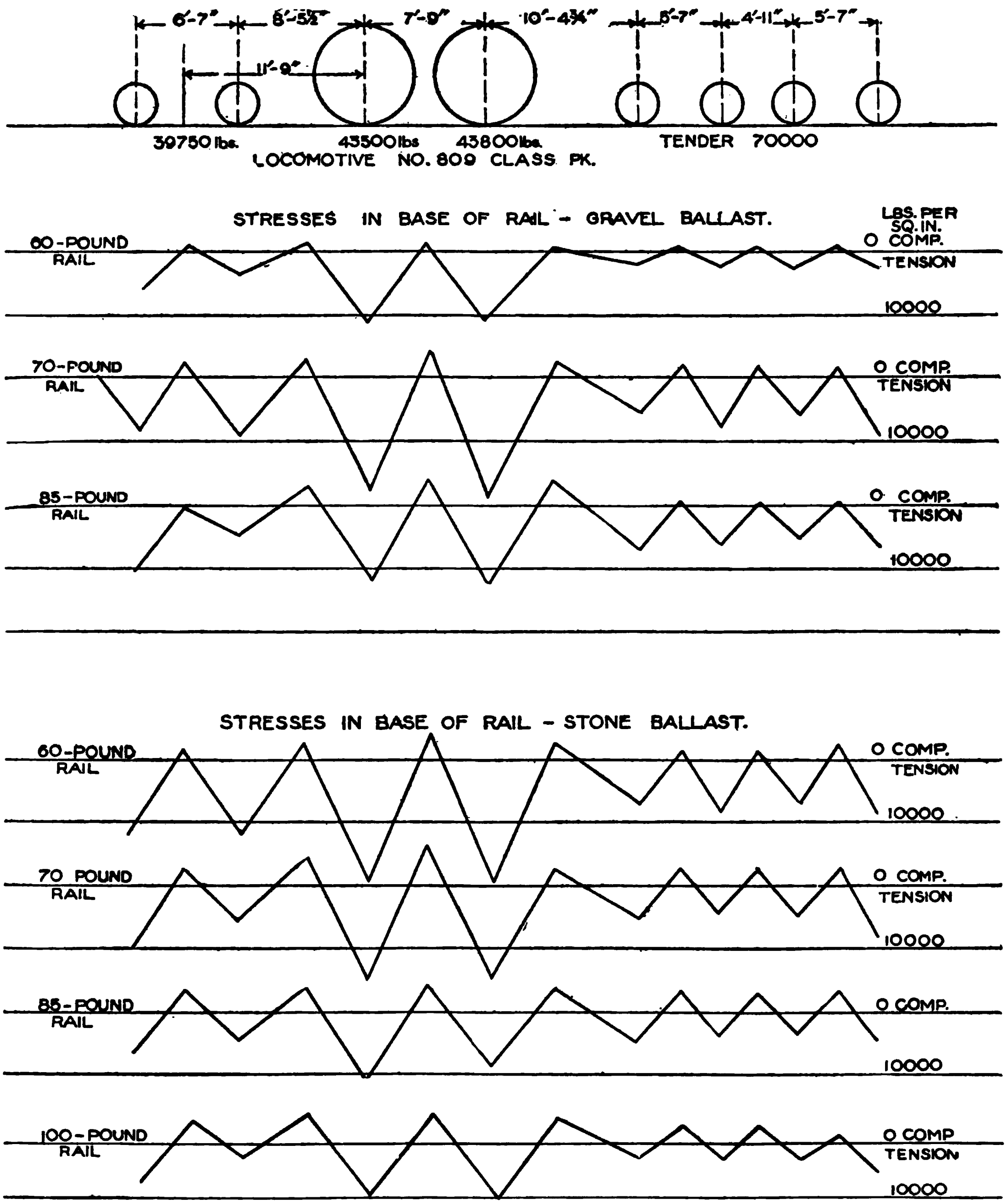


FIG. 167. — Railroad Track Experiments, Pennsylvania R. R. Stress in Rail.

All of the experiments just described have been made with the static load of the engine. In 1897, Dr. P. H. Dudley commenced a series of interesting tests to determine the effect of the dynamic load of the engine.

* In Figs. 168 and 169 are shown the results of tests made by Dr. Dudley with the stremmatograph. The principle of the stremmatograph is to record on a moving strip the molecular compression or elongation of the metal in a given length of the base of the rail, induced by the strains produced by each

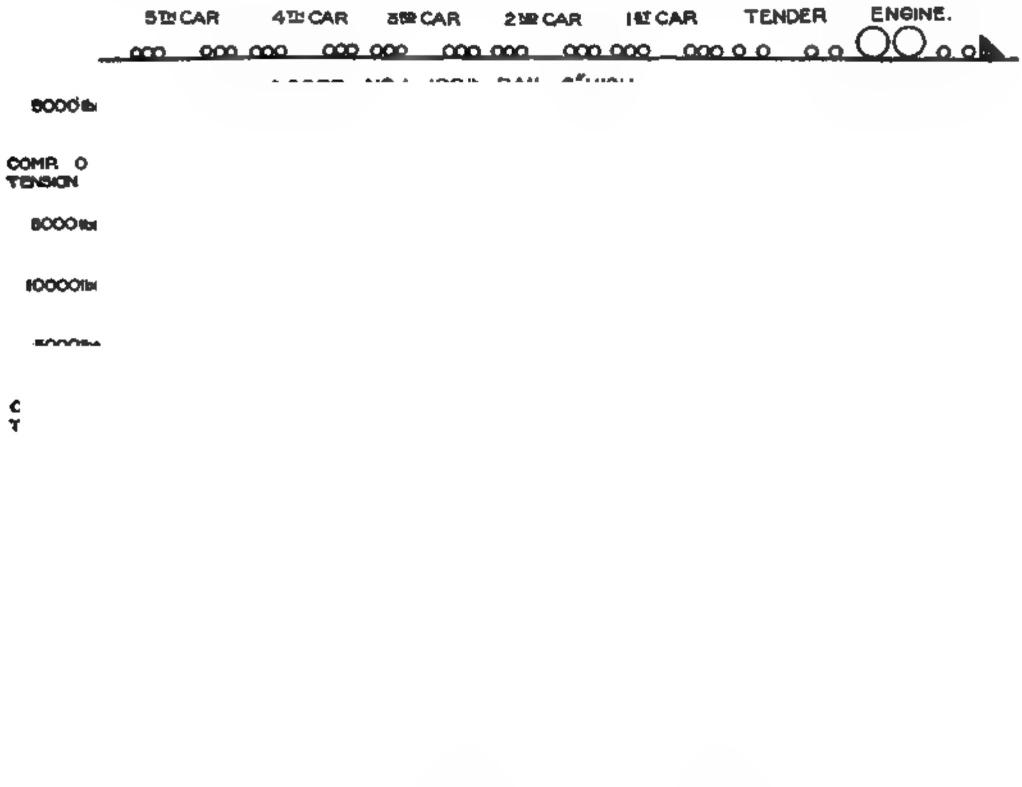


Fig. 168. — Stremmatograph Tests at 19 and 40 m.p.h.

wheel of the moving train. These records can be measured by filar-micrometers under a microscope, and then from the modulus of elasticity of the steel we may compute the stresses which produce the given compression or elongation per square inch of the extreme fiber in the base of the rail.

The object of the stremmatograph is to convert rails of any section and weight, of any system of permanent way construction, into testing machines in the track and show how much they are strained, due to the wheel loads and

* Dr. P. H. Dudley, The Railroad Gazette, May 20 and October 21, 1898, Stresses in Rails under Moving Loads. Vol. III, Proceedings Am. Society for Testing Materials, 1903, Stremmatograph Tests, by P. H. Dudley. Vol. IV, ibid., 1904, Bending Moments in Rails, by P. H. Dudley.

spacing of any type of locomotives and cars moving over the rails at the different speeds of service. In principle it is the same as the device for measuring the strain in bridge members, described in Article 9.

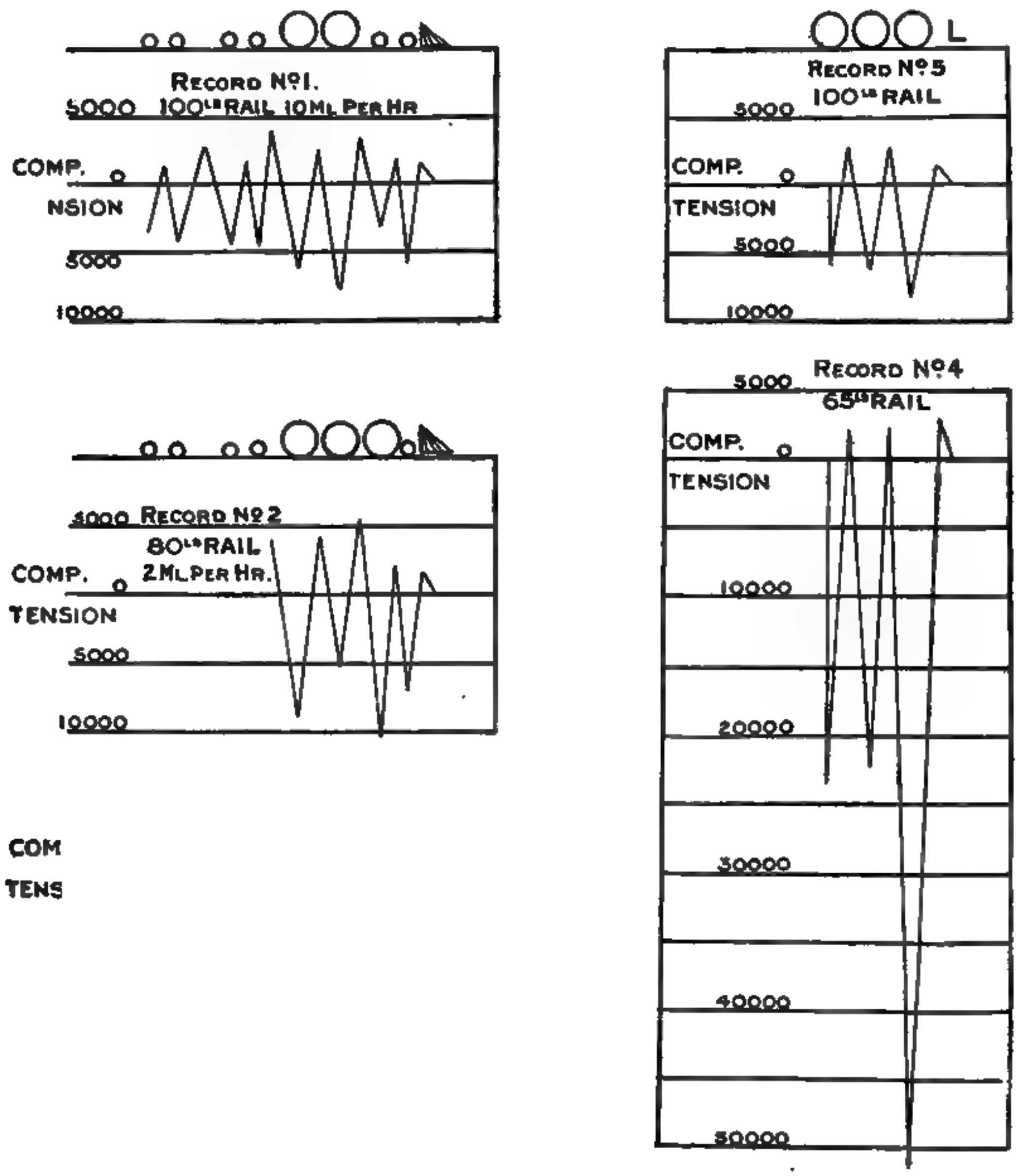


FIG. 169 — Stremmatograph Tests at Slow Speeds.

Record No. 1, Fig. 168, is taken on the New York Central and Hudson River Railroad tracks. The instrument was applied on the outside rail of a 3-degree curve at the Grand Central Terminal, over which nearly all of the heavy trains from the terminal pass outward; the tonnage was from 20,000 to

25,000 per day, and there was more looseness in the track than generally found out on the main line. The following is the data of the test.

Date,	June 28, 1898.
Weight of rail,	100 pounds per yard.
Height of rail,	6 inches.
Ballast,	Stone.
Ties,	Oak with tie plates spaced 24 inches, center to center.
Speed, miles per hour,	19.
Temperature,	90° F.
Locomotive and tender,	202,000 pounds.
First car,	95,000 pounds.
Second car,	86,200 pounds.
Third car,	82,000 pounds.
Fourth car,	94,950 pounds.

Record No. 1, Fig. 169, shows the extreme fiber stresses in the same track and under the same engine in a test of December 29, 1897, temperature 23° F., when the engine was moving at a speed of 10 miles per hour.

When the December test was made, the rail was not only firm on the ties but was under some tension, due to the low temperature. In this test the small stresses under the front truck wheel show at once that the rail was very firmly supported and was not loose on the ties. The rail being under tension before loading, the actual stresses of tension in the rail were higher than indicated, and those of compression lower.

When the June tests were made, the track had not been tamped or surfaced by the trackmen since the preceding October. Over 16,000,000 tons had been carried over the rails since that date, or 12,000,000 tons since the previous test.

Since the December test, air brakes had been applied to the engine trucks, which adds more to her weight. While the engine truck carried more weight in the June than in the December test, the increased stresses under the front truck wheels and the much larger stresses of compression show that the rail and ties were much looser in the June test.

Record No. 2, Fig. 168, was taken at West Albany (N. Y. C. & H. R. R. R.) September 30, 1897. The engine was drawing five Wagner palace cars at a speed of 40 miles per hour; 80-pound rail, 5 inches high; ties spaced 25 inches, center to center.

Records Nos. 2 and 3, Fig. 169, show tests made at 2 miles per hour and 10 miles per hour. The total weight of the locomotive was 96 tons; the engine 60 tons, with 15,500 pounds on pony truck and 104,500 pounds on three pairs of drivers. The tender weighed 72,000 pounds. The instrument was placed on the outside rail on a 3-degree curve and down grade of 10 feet per mile. The rail was 80-pound section, $5\frac{1}{8}$ inches high. The ties were yellow pine, 7 by 9 inches, spaced 25 inches, center to center. Gravel ballast, the track being in good condition. 30,000,000 pounds was taken as the modulus of elasticity of the steel.

The two ties between which the stremmatograph was attached to the rail were very firm in the ballast, and to the eye did not seem to depress as much as those on either side; therefore the compression strains were probably higher than on ties all practically depressing alike in the ballast.

Records Nos. 4 and 5, Fig. 169, were taken on 65-pound and 100-pound rails, respectively. The 65-pound rails were of steel with an elastic limit of 60,000 pounds, while on the 100-pound rails it was 65,000 pounds. The locomotive was a switching engine, having 125,000 pounds upon drivers. The instrument was placed between ties spaced 30 inches, center to center, having tie plates.

Dr. Dudley states that tests with his stremmatograph show that the bending moments in 80-pound rails under wheel loads used in 1905 may be as high as 300,000 to 350,000 inch-pounds, indicating a unit fiber stress in the base of the rail of as much as 30,000 or 35,000 pounds on worn 5-inch 80-pound sections. With the 65-pound rail, stresses were frequently found as high as 40,000 to 45,000 pounds.*

23. Calculation of the Bending and Shearing Stress in the Rail

Examining, first, the moment and shear in the rail between two pairs of driving wheels, we see that if the rail were completely rigid there would result a uniform distribution of the wheel pressure to the ties, and if w equal the pressure of one wheel divided by the wheel spacing, l, the resulting moment and shear in the rail would then be

$$\text{Maximum moment, } M = \frac{1}{12} wl^2,$$

$$\text{Maximum shear, } J = \frac{wl}{2}.$$

From the discussion on the support of the rail, we can take .35 ton as a maximum value for w, and 150 inch-tons will be taken, for the present, as

* Private communication, June 7, 1912.

the maximum allowable moment, the following calculations being based on 100-pound A. S. C. E. rail. From the above we may construct the dotted line shown in Fig. 170.

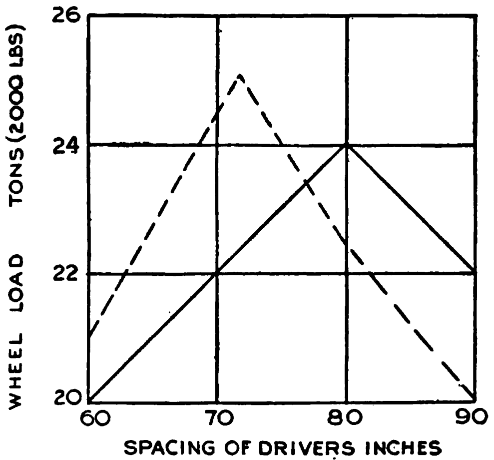


FIG. 170. — Wheel Loads for Different Spacing of Drivers.

Considering, now, the effect of the unequal distribution of the wheel pressure to the ties: Fig. 142 shows the relation of the reaction of the tie to the depression in the ballast. We can, therefore, by constructing the elastic curve of the rail to give a shear curve corresponding to the support of the tie, given in Fig. 142, obtain the true elastic curve of the rail, from which the moment and shear diagrams can be developed.

By this method we will assume the probable curve of the rail and from this curve deduce the moment and shear curves. The shear curve will give the reactions under the rail, and by comparing these with the pressure exerted by the ties for the given depression, as shown by the curve of the rail, the correctness of the latter can be checked. After a few trials the actual curve taken by the rail for any span and wheel load can be drawn, and the maximum bending moment and pressure on the ballast ascertained.

Mr. C. E. Love of the University of Michigan has made a very interesting analysis of the results of the government tests of 1889, 1894, and 1895, described in Article 22. As it is proposed to use the method adopted by Mr. Love a review of one of the cases he has worked out will prove instructive and, on account of the careful measurements made in the test selected, the accuracy of the analysis can be shown before proceeding with its application to the general case under consideration.

In Mr. Love's discussion the elastic curve of the rail, plotted from the careful measurements given in these tests, is taken as the original curve, and the curve of slopes, bending moment diagram, and shear diagram derived by the following relations:

$$\text{Elastic curve, } v = f(x), \text{ or } \frac{v}{x},$$

$$\text{Curve of slopes, } C = f'(x), \text{ or } \frac{dv}{dx},$$

$$\text{Moment diagram, } M = EIf''(x), \text{ or } EI\frac{d^2v}{dx^2},$$

$$\text{Shear diagram, } F = EIf'''(x), \text{ or } EI\frac{d^3v}{dx^3}.$$

Plate XXIII shows one of the diagrams worked out by Mr. Love. This plate is based on diagram No. 5 of the 1894 experiments.* The rail used was 30 feet long, with tie centers at points 1, 2, 3 - - - - 18 (diagram A) and loaded as shown, one horizontal space representing 2 inches.

In diagram B, points on the elastic curve were plotted from the observed deflections and a smooth curve drawn through them, one vertical space representing a deflection of .002 inch. This curve was then divided into segments 6 inches (three spaces) in length along the horizontal axis and the slope of each segment measured as if it had been straight. In determining the tangent of each slope angle, the measurements were made in sixtieths of an inch. The base, of course, was constant, three spaces equaling $\frac{14}{60}$ inch of actual distance on the paper, so that, calling the altitude dv, the actual slope was $\tan = \frac{dv}{14}$, where dv was measured in sixtieths of an inch. In drawing the slope curve, diagram C, however, one space corresponded to an altitude of $\frac{1}{60}$ inch. For example, the extreme left-hand segment, diagram C, is three spaces below the axis. This makes the value of one space in diagram C,

$$1 \text{ space} = \frac{2}{1000} \cdot \frac{1}{2} \cdot \frac{1}{14} = \frac{1}{14{,}000}.$$

The bending moment was constructed by plotting points directly from diagram C, by taking the ordinates of the bending moments equal to the corresponding breaks in the slope curve. The ordinates of the points in diagram D are three times the actual slope of the curve in diagram C. The moment of inertia (I) of the rail is 19.127, and a value of the modulus of elasticity (E) is taken as 30,000,000.

Hence, since $M = EI\frac{d^2v}{dx^2}$, we have for the value of one space in diagram D,

$$1 \text{ space} = \frac{1}{14{,}000} \cdot \frac{1}{3} \cdot \frac{1}{2} \cdot 30{,}000{,}000 \times 19.127 = 6800 \text{ inch-pounds.}$$

The construction of diagram E is now very simple. The actual slope of a segment of the moment curve was measured and the ordinate of the shear curve taken as 10 spaces for each unit of the measured slope. Hence, for diagram E,

$$1 \text{ space} = 6800 \cdot \frac{1}{10} \cdot \frac{1}{2} = 340 \text{ pounds.}$$

The bending moment at any point can now be scaled directly from diagram D, and the change in shear under any tie in diagram E is the reaction at the tie.

The total load on this rail is 56,500 pounds. After examining the re-

* House Executive Documents, 3rd Session, 53rd Congress, 1894–95, Vol. 30, Tests of Metals, etc.

actions at ties 1, 2, and 3, it is reasonable to suppose that 3000 pounds of the load at No. 1 is supported by the rail to the left, thus leaving a net load of 53,500 pounds. The total upward reaction is 52,300 pounds.

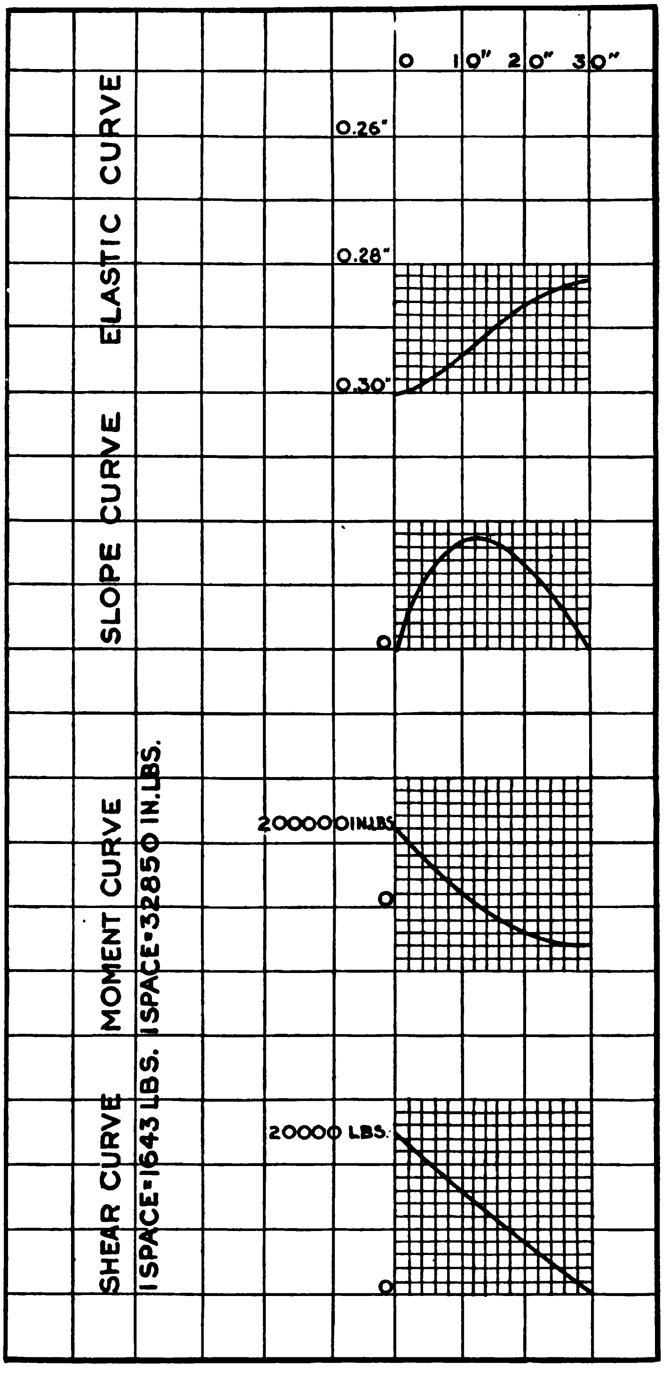


Fig. 171. — Rail Diagram for Wheel Spacing of 60 inches, two-thirds size of original diagram.

The error at No. $5\frac{1}{2}$ is 100 pounds, i.e., the actual load is 16,000 pounds, while as read from diagram E it is 16,100 pounds; at No. $10\frac{1}{2}$ the error is + 300 pounds; at No. $13\frac{1}{2}$, + 300 pounds.

Other experiments were performed on this rail, in which the fiber stresses were measured. The maximum bending moment here is +98,500 inch-pounds. In the other experiments it was 117,000 inch-pounds, caused by an engine 10 per cent heavier, with the load at the middle of a 24-inch span. The minimum here is − 24,000 inch-pounds; in the other experiments it was − 38,500 inch-pounds.

Fig. 171 shows the construction for 100-pound A. S. C. E. rail with spans of 60 inches, between centers of driving wheels.

The construction of Fig. 171 is similar to that of Plate XXIII. The scale to which the elastic curve is drawn is, 0.002 inch equals one space vertically, and 2 inches equals one space horizontally. In deriving the slope curve, the actual ordinates of the elastic curve are measured in fiftieths of an inch, and one vertical space on the slope curve is taken to represent one-fiftieth of an inch of the elastic curve ordinate. The base is taken in all the curves as two spaces.

The value of one vertical space of the slope curve is, then,

$$\frac{2}{1000}\cdot\frac{1}{50}\cdot\frac{1}{\left(\frac{2}{10}=\frac{10}{50}\right)}\cdot\frac{1}{2},$$
$$\frac{2}{1000}\cdot\frac{1}{50}\cdot\frac{50}{10}\cdot\frac{1}{2},$$
$$\frac{2}{1000}\cdot\frac{1}{10}\cdot\frac{1}{2}=\frac{1}{10{,}000}.$$

For example, the ordinate of the elastic curve at 2 inches to the right of the wheel is about $\frac{5}{50}$ inch; the actual slope is, therefore, $\tan = \frac{5}{50} \div \frac{2}{10}$ or $\frac{5}{50} \div \frac{10}{50} = .5$, as shown by the slope curve between 0 and 2 inches. The ordinate of the elastic curve at 4 inches is about $\frac{12.5}{50}$ or the rise from 2 inches to 4 inches is $\frac{7.5}{50}$ and the slope .75, as appears on the slope curve, between 2 inches and 4 inches.

The ordinates on the moment curve are taken the same number of spaces as the corresponding breaks in the curve of slopes and consequently, on account of the base being 2 spaces, represent twice the actual slope of the slope curve. The value of one vertical space in the moment curve is, then,

$$\frac{1}{10{,}000}\cdot\frac{1}{2}\cdot\frac{1}{2}\,EI.$$
$$\frac{1}{10{,}000}\cdot\frac{1}{2}\cdot\frac{1}{2}\cdot 30{,}000{,}000 \times 43.8 = 32{,}850 \text{ inch-pounds.}$$

The ordinates of the shear curve are five times those of the moment curve, and the value of one vertical space in the shear curve is

$$32{,}850\cdot\frac{1}{5}\cdot\frac{1}{2}\cdot\frac{1}{2} = 1643 \text{ pounds.}$$

The most simple way to construct the diagram is to approximate the elastic curve of the rail and then follow out the operations, as shown by Table LX, correcting the elastic curve from column 11 of the table and readjusting the calculations, if necessary, to the corrected elastic curve values.

TABLE LX.—CALCULATIONS OF RAIL DIAGRAMS FOR 60-INCH WHEEL SPACING

Horizontal distance.	Depression below track-man's surface.	Load.	Shear.		Moment.		Slope.		Elastic curve in $\frac{1}{16}$ inch.	
Inch.	Inch.	Pounds.	Pounds.	Spaces.	2×tan.	Ordinate.	2×tan.	Ordinate.	2×tan.	Ordinate.
1	2	3	4	5	6	7	8	9	10	11
0	0.30	....	20,080	12.2	2.44	6.1	....	0	0	0
2	....	2800	....	....	....	4.9	4.9	....	....	2.5
4	....	....	17,280	10.5	2.10	....	....	4.9	4.9	
6	....	2760	....	....	....	2.8	2.8	....	....	7.4
8	....	....	14,520	8.8	1.76	....	....	7.7	7.7	
10	....	2720	....	....	....	1.0	1.0	....	....	15.1
12	....	....	11,800	7.2	1.44	....	....	8.7	8.7	
14	....	2680	....	....	....	− .4	− .4	....	....	23.8
16	0.29	....	9,120	5.6	1.12	....	....	8.3	8.3	
18	....	2640	....	....	....	−1.5	−1.5	....	....	32.1
20	....	....	6,480	3.9	.78	....	....	6.8	6.8	
22	....	2610	....	....	....	−2.3	−2.3	....	....	38.9
24	....	....	3,870	2.4	.48	....	....	4.5	4.5	
26	....	2590	....	....	....	−2.9	−2.9	....	....	43.4
28	0.28¼	....	1,280	0.8	.16	....	....	1.6	1.6	
30	....	1280	....	....	....	−3.1	−3.1	0	0	45.0

Note. — Col. 3 is found from col. 2 and Fig. 142.
Col. 4 is found from col. 3 and is the total load carried from the center of the span.
Col. 5 is found from col. 4 by dividing the figures given in col. 4 by 1643.
Col. 6 is found from col. 5 by dividing the figures given in col. 5 by 5.

In Fig. 172 are given diagrams for spans of 70 inches, 80 inches, and 90 inches between centers of drivers.

The maximum bending moment can be read directly from the moment curve and the wheel load is twice the load supported on half the span or twice the total reaction shown by the shear curve of the diagrams. In comparing the shear curve with the curve of pressures of the ties it would seem desirable to assume the rail to be supported by a distributed load in place of a series of loads concentrated at the ties, the effect will be practically the same and the calculations much simplified.

The results of static and dynamic tests of the stress in the rail both indicate that the negative bending moment between the drivers is very much smaller than the positive bending moment produced in the rail under the drivers. The dynamic tests appear to show a ratio of about 1 to 4 or a compressive stress in the base of the rail only one-fourth as great as the tensile stress, under normal conditions. In poorly tamped track the compression stress seems to increase.

If the rail were uniformly supported between the wheels the compression stress would be one-half the tension stress under the wheels of a set of drivers.

Such a condition of the pressure exerted by the tie would be represented by a horizontal line in Fig. 142. The diagrams given in Figs. 171 and 172 show that, as the spacing of the drivers increases, the negative bending moment or the compression stress in the base of the rail decreases in relation to the tension

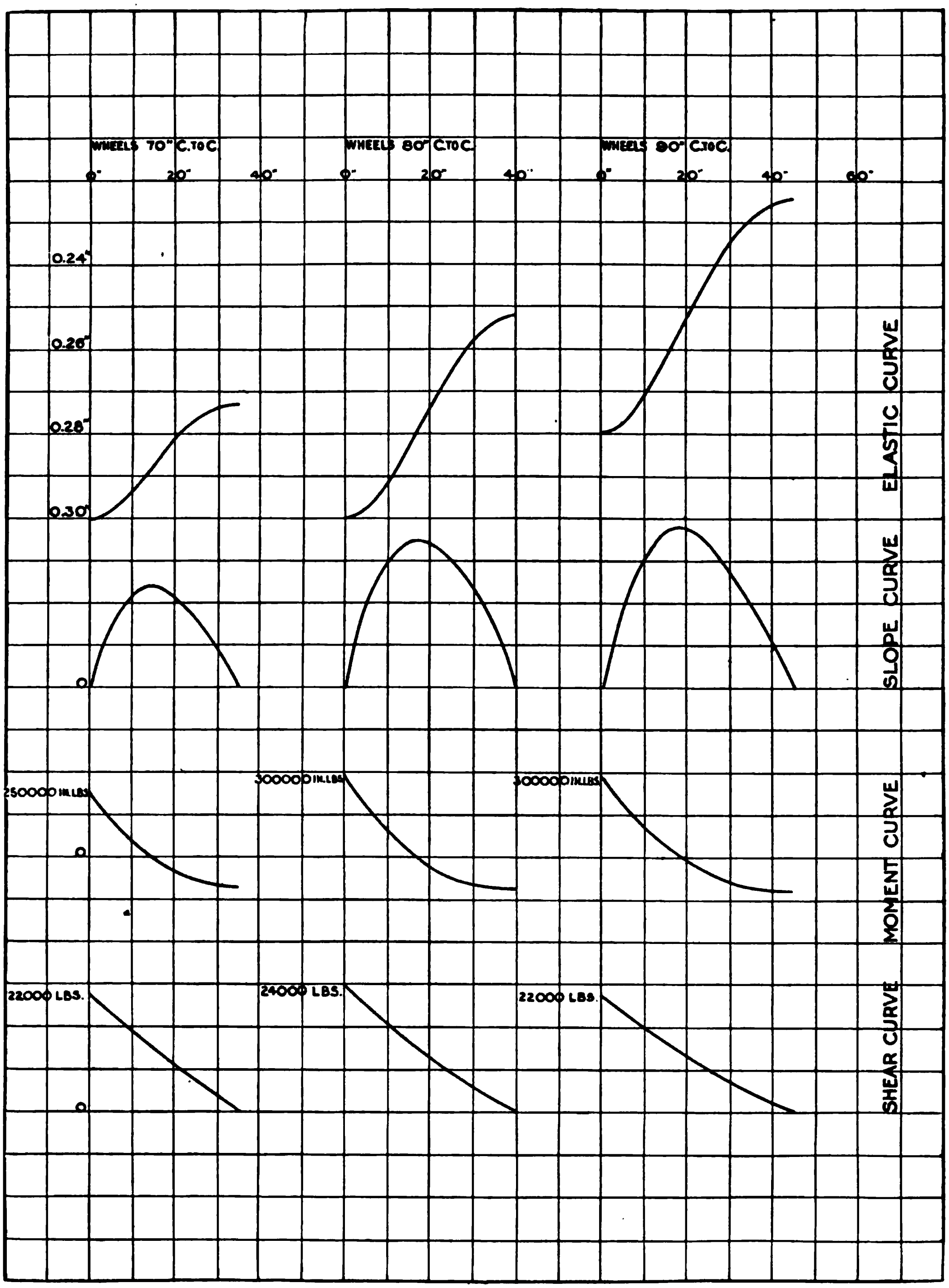


FIG. 172. — Rail Diagram for Wheel Spacing of 70, 80, and 90 inches, one-half size of original diagram.

stress; for drivers spaced 60 inches apart it is practically one-half the tensile stress, but when the spacing is increased to 90 inches it is not much more than one-third.

An examination of Fig. 142 makes this clear and shows that with the greater deflection obtained in the 90-inch span the ties in the center of the span support relatively much less of the load. With lighter rail the deflection would be still further increased and a greater ratio of the tension to the compression stress obtained.

The full line, shown in Fig. 170, shows the true allowable wheel loads given by the diagrams of Figs. 171 and 172. Up to spans of 80 inches the wheel load is limited by the safe bearing power of the tie and is obviously less than that obtained from the assumption that there is a uniform distribution of the wheel pressure to the ties upon which the dotted line of Fig. 170 is based. After the spacing of the drivers exceeds 80 inches the wheel load is limited by the bending moment in the rail; here the bending moment is greater for a uniformly distributed load and, consequently, the dotted line in the figure falls below the full line.

Turning our attention to the allowable wheel load as determined by the conditions at the front and rear drivers. Figs. 162 and 163 show that there is a wave motion of the rail ahead of the engine and the rail rises slightly above the trackman's surface. This lack of pressure on the rail at the outside wheels causes these wheels to exert a more severe action on the rail. This is clearly shown by Table LVIII and in Fig. 162, where the outside drivers, although carrying less weight, gave practically the same stress as the middle driver. Records Nos. 2 and 3 of Fig. 169 illustrate the same tendency.

The rail diagrams, just worked out, show that in increasing the wheel spacing from 80 to 90 inches the permissible wheel load fell from 24 to 22 tons. From the diagram for the 90-inch wheel spacing it is seen that the ties in the middle of the span afford little support, and while it is somewhat problematic what load will be carried by the rail ahead of the front driver, we will not be very far wrong if we assume it to carry 8 tons with no leading truck, 9 tons with a two-wheel leading truck, and 10 tons with a four-wheel leading truck.

On account of the load of the tender wheels and the effect of the drawbar pull, we may reasonably take 10 tons where a trailing truck is used and 9 tons where there is no trailer, as the load carried by the rail back of the rear drivers.

Table LXI may now be prepared showing the allowable dynamic wheel load under different conditions of wheel spacing.

TABLE LXI.—ALLOWABLE DYNAMIC WHEEL LOAD (POUNDS) FOR 100-POUND A. S. C. E. RAIL

Spacing of Drivers:	60 Inches.	70 Inches.	80 Inches.	90 Inches.
Middle wheel	40,000	44,000	48,000	44,000
Front wheel,				
No leading truck	36,000	38,000	40,000	38,000
Two-wheel leading truck	38,000	40,000	42,000	40,000
Four-wheel leading truck	40,000	42,000	44,000	42,000
Back wheel,				
No trailing truck	38,000	40,000	42,000	40,000
Trailing truck	40,000	42,000	44,000	42,000

Referring to Figs. 31 and 32, of typical load diagrams of engines, it will be seen that with the exception of the articulated engine there is had a very satisfactory agreement between Table LXI and the diagrams.

We have now to consider the stresses in the rail caused by the bending moment and shear derived in Figs. 171 and 172. The maximum bending moment in these figures is 300,000 inch-pounds, and the maximum shear is 24,000 pounds.

It is beyond the scope of the present work to enter into the discussion of mathematical investigations of continuous web strains, and in order to form some conception of the nature of stresses in the continuous rail we shall view the matter in the simplest manner possible.*

In the rail under the wheel it is evident that, by virtue of the bending stress, that part of the rail above the neutral axis is subject to compression, and that below to tension, both of which stresses attain maximum values at the outermost fibers of the rail, and decrease to zero at the neutral axis. This intensity of the stress at any point is at once obtained from the well-known equation of flexure:

$$\frac{M}{I} y = f, \qquad \text{(a)}$$

where M is the bending moment, I the moment of inertia of the section of the rail, y the distance of the point from the neutral axis, and f the intensity of the stress at that point.

Table LXII gives the extreme fiber stress in the base due to bending in different sections of 100-pound rail, caused by a bending moment of 300,000 inch-pounds. The high moment of inertia in the Series "A" of the American Railway Association would give a slightly different elastic curve for this rail than is shown for the A. S. C. E. section in Figs. 171 and 172, with the result

* See Plate Girder Construction, Isami Hiroi, New York.

that the bending moment would be increased and the unit of load supporting the rail decreased.

TABLE LXII.—EXTREME FIBER STRESS DUE TO A BENDING MOMENT OF 300,000 INCH-POUNDS

Section.	Weight.	Extreme Fiber Stress.
	Pounds per Yard.	Pounds per Square Inch.
A. S. C. E.	100	18,600
Am. Ry. Assn., Series "A"	100	16,900
Am. Ry. Assn., Series "B"	100	19,100

The bending moment M decreases as we proceed toward the center of the space between the wheels, and with it evidently the intensity f of the horizontal stress also; so that f varies not only in vertical directions on both sides of the neutral axis, but also in the direction of the length of the rail.

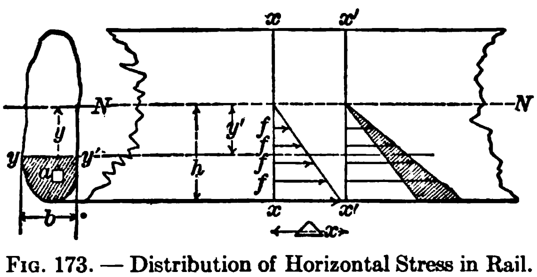


FIG. 173. — Distribution of Horizontal Stress in Rail.

Let xx and $x'x'$, in Fig. 173, be two sections of a rail, very close to each other, and NN the neutral axis.

The variation of the value of f in both sections may be represented by triangles with apices in the neutral axis, and the variation in the longitudinal direction between these two sections by the difference of the areas of two triangles, as shown shaded in the figure. This increase of horizontal stress from one section to another produces at each longitudinal layer a force tending to slide it past the layer next above it, and is transmitted undiminished toward the neutral axis, where this shearing force, which has been increasing at every layer, attains its maximum intensity.

This stress is called the longitudinal shear, and can be at once obtained from equation (a). Thus, let f' be the corresponding value of f in section $x'x'$; and let M and M' be the bending moment in the two sections xx and $x'x'$ respectively, and a an infinitely small cross area, distant y from the neutral axis. The total horizontal stresses acting in that part of the section lying between the extreme fiber distant h from the neutral axis and the layer $y'y'$ distant y' from the axis in xx and $x'x'$ are respectively:

$$\sum_{y'}^{h} fa, \qquad \sum_{y'}^{h} f'a.$$

The longitudinal shear in the layer $y'y'$ between the two sections is, therefore, equal to

$$\sum_{y'}^{h} f'a - \sum_{y'}^{h} fa.$$

Substituting in the expression the values of f and f' given by equation (a), we obtain,

$$\sum_{y'}^{h} f'a - \sum_{y'}^{h} fa = \frac{M' - M}{I} \sum_{y'}^{h} ya.$$

Since the area on which this horizontal shear is acting is equal to $b\,\Delta x$, when b is the breadth of the cross section at the layer $y'y'$ and Δx the distance between x and x', we obtain for the intensity of the shear,

$$\frac{M' - M}{Ib\,\Delta x} \sum_{y'}^{h} ya. \tag{b}$$

Thus at every point in the rail there are two shearing actions taking place at the same time, one the longitudinal shear and the other the vertical shear.

Imagine *abcd*, Fig. 174, to be an infinitely small portion of the side of a rail at a point distant y' from the neutral axis. Suppose the side of this area element to be Δx and Δy, and the breadth of the beam at the point to be b. There are then found two shearing stresses on this element, one vertical and the other horizontal.

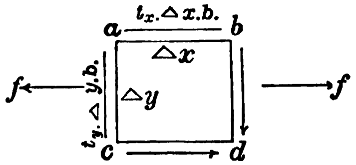


FIG. 174.—Shearing Stress of Point Distant y' from Neutral Axis.

These two shears form two pairs of couples acting around the body, as shown by the arrows. Let t_x represent the intensity of the horizontal shear at this point and t_y that of the vertical. The amount of the horizontal shear is equal to $t_x\,\Delta x\,b$; that of the vertical shear is likewise equal to $t_y\,\Delta y\,b$.

In order that the body be in equilibrium, the moment of these couples must be equal, i.e., $t_x\,\Delta x\,b\,\Delta y = t_y\,\Delta y\,b\,\Delta x$. Consequently, $t_x = t_y$ (which is always the case), showing that at every point in the rail the intensities of the vertical and horizontal shears are equal, and we will hereafter designate them with the common letter t. The value of t_x has already been deduced in equation (b), namely:

$$t = \frac{M' - M}{b\,\Delta x\,I} \sum_{y'}^{h} ay. \tag{c}$$

But the value of $\dfrac{M' - M}{\Delta x} = S_x$, where S_x is the total vertical shear at the section x. Substituting this value of $\dfrac{M' - M}{\Delta x}$ in equation (c), there results:

$$t = \frac{S_x}{bI} \sum_{y'}^{h} ay, \tag{d}$$

or the intensity of the shearing stress at any point in the rail is equal to the total shearing force on the entire cross section multiplied by the statical moment of the area of the section outside the longitudinal plane of shear in question about its axis in the neutral plane, divided by the product of the moment of inertia of the entire section into the breadth of the section at that point.

Fig. 175 shows the intensity of the shearing stress in a 100-pound rail, the total vertical shear at the section being 24,000 pounds.

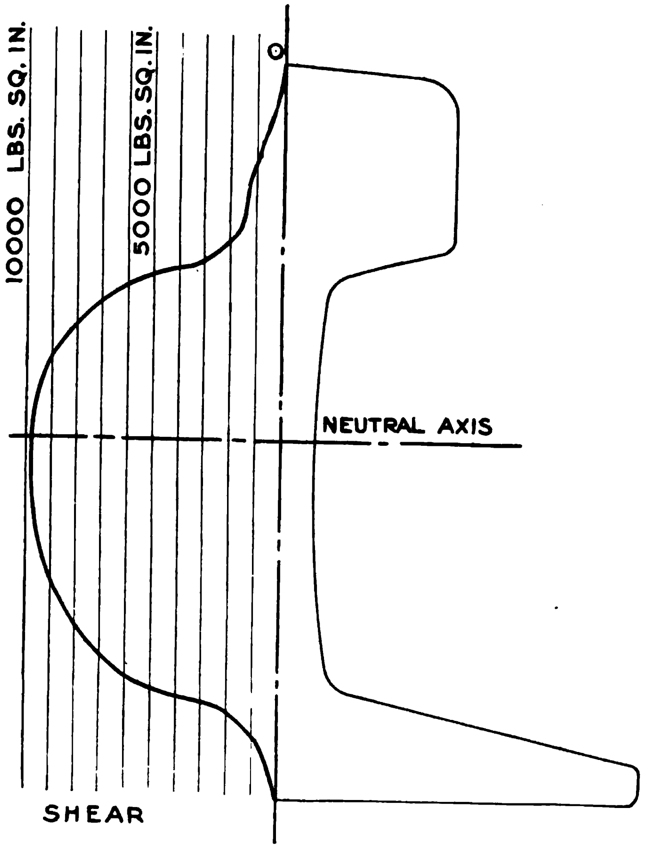


FIG. 175. — Shearing Stress in 100-pound A. S. C. E. Rail.

There still remains to be considered the horizontal force f, whose value is given in equation (a), tending either to compress together or pull asunder the two faces ac and bd (Fig. 174), according as it is on the upper or lower side of the neutral axis.

At the neutral axis where $f = 0$, t_x and t_y are then the only stresses, and we know from mechanics that the resultant action of two equal shears at right angles to each other, exactly as t_x and t_y are, is equivalent to that of two equal and opposite stresses at right angles to each other, called the principal stresses and making an angle of 45° with the shearing stresses. But at a distance each

side of the neutral axis the third stress, f, now comes in, which evidently gives a new direction to the line of resultant stress, turning the axis of principal stresses toward itself more and more as its intensity increases.

Fig. 176 represents the appearance which the lines of principal stresses thus obtained present in a beam loaded in the middle and supported at each end. The lines of maximum tension are shown dotted and cut the lines of compression always at right angles. Both lines cross the neutral axis at an inclination of 45° and run almost parallel to it in the middle of the beam in the neighborhood of extreme fibers.

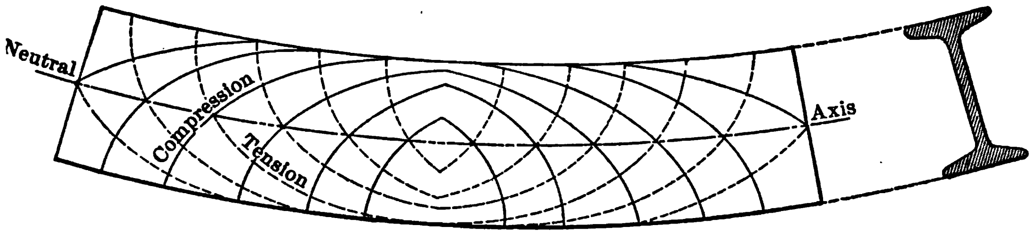


FIG. 176. — Lines of Principal Stress in Beam.

Now comes the question how the web should be proportioned to resist such stresses: The greatest intensity of the vertical shearing stress on the vertical section of the rail, shown in Fig. 175, is about 10,000 pounds per square inch. In modern bridge practice a shearing stress is allowed in web plates of 10,000 pounds per square inch, which gives a satisfactory thickness of the web for the rail shown in the figure. But as has already been explained, the action of the shearing stresses at the neutral axis is equivalent to compression and tension at right angles to each other and of equal intensity, making an angle of 45° with the axis, and the web is still in danger of failing by flexure under this compression stress.

Consequently, the web with its thickness as already proportioned for shearing must now be examined for its strength as a column. We will probably be not far from correct if the length of the column is taken as h sec 45°, h being the vertical distance between the top of the flange and bottom of the head of the rail. Then, for the 100-pound A. S. C. E. rail, h sec 45° equals 4.4 inches, and the load is

$$\frac{P}{A} = p = 10{,}000 \text{ pounds per square inch.}$$

This amount is correct for the bending stress caused by the load which is central over the rail head. The wheel load is, however, rarely applied exactly in line with the vertical axis of the rail, and the additional couple due to the eccentricity causes a torsion in the rail. To make a correct analysis would

be very complicated and decidedly uncertain on account of the lack of experimental evidence.

No column formula can be made to apply exactly to the web of the rail. If we apply the formula for a column with an eccentric loading of .6 of an inch, the resulting stress amounts to over 50,000 pounds per square inch. It is doubtful, however, whether the stress introduced by this torsion can be combined with those due to bending in this manner.

It will be observed that, even were this large stress correct, there is a tensile stress acting at right angles to the compression stress and tending to hold the strip in its true plane. Just what the restraining influence of this tensile stress is cannot be determined theoretically, but the following experiments show it to be of importance.

During 1910 tests were made at the Maryland Steel Company's plant at Sparrows Point, Md., for the purpose of determining what effect the eccentric loading of the wheel had on the head and web of the rail.* The tests were made with a 200,000-pound test machine by canting a piece of rail 18 inches long and applying the load at the edge by means of a block with a radius of $16\frac{1}{2}$ inches, to represent a car wheel, where it came in contact with the rail. Other tests were made with a reciprocating machine representing a loaded wheel rolling back and forth on the edge of the canted rail.

For the tests a rail was taken from stock and six pieces each 18 inches long were cut from it for test in the stationary test machine and six similar pieces were used for test in the reciprocating machine. In order to have the material as uniform as possible throughout the section and in the different pieces, a " C " rail was selected, that is, the third rail from the top of the rail bar. The rail was a 90-pound A. R. A. type B section and the pieces were planed down to thicknesses of head at the side of $\frac{3}{8}$ inch, $\frac{1}{2}$ inch, $\frac{5}{8}$ inch, $\frac{3}{4}$ inch, $\frac{7}{8}$ inch, and 1 inch, two pieces of each thickness, one for each kind of test. In each case the brand side of the head of the rail, which was the bottom side as rolled, was planed vertical to a width of $1\frac{3}{16}$ inches from the center line. Fig. 177 shows the dimensions of the section used and also gives diagrams of the pieces tested. The essential dimensions of the head of the pieces tested, as indicated by letters *A*, *B*, and *C*, on Fig. 177, measured as shown in Table LXIII.

Two samples were taken with a $\frac{1}{2}$-inch drill for analysis from a section near the middle of the length of the rail, one close to the upper corner and the other at the junction of the head and the web. The results of the analyses are shown in Table LXIV.

* Strength of Rail Head, M. W. Wickhorst, Proceedings Am. Ry. Eng. & M. of W. Assn., 1911, Vol. 12, Part 2, p. 518.

These results show the material to be very uniform.

TABLE LXIII. — DIMENSIONS OF HEADS AS TESTED FOR STRENGTH OF RAIL HEAD

Test Numbers.	Thickness of Head.		Width.
	Edge, *A.*	Center, *B.*	Side to Center, *C.*
1 and 2	1.02	1.26	1.15
3 and 4	.91	1.15	1.18
5 and 6	.76	1.02	1.17
7 and 8	.62	.86	1.15
9 and 10	.51	.75	1.16
11 and 12	.38	.64	1.17

TABLE LXIV. — ANALYSES OF RAILS TESTED FOR STRENGTH OF RAIL HEAD

	Corner of Head.	Junction of Head and Web.
Carbon	.538	.523
Phosphorus	.070	.070
Sulphur	.050	.055
Manganese	.81	.81
Silicon	.103	.103
Copper	.19	.18
Nickel	None	None
Chromium	None	None

Tensile tests were also made of pieces cut from near the middle of the rail, two pieces ½-inch diameter and 2-inch gauge length, for longitudinal test from the center of the head, and two pieces ½-inch diameter and 1-inch gauge length for transverse test across the center of the head. The yield point in the 2-inch pieces was determined by means of a Capp's multiplying dividers. The results of the tests are shown in Table LXV.

TABLE LXV. — TENSILE TESTS OF RAILS TESTED FOR STRENGTH OF RAIL HEAD

	Yield Point (Pounds per Square Inch).	Tensile Strength (Pounds per Square Inch).	Elongation.	Reduction of Area.
Longitudinal . . . *a*	51,000	111,600	16	29
2-inch gauge length . . . *b*	52,700	111,500	16.5	29
Average	51,850	111,550	16.3	29
Transverse . . . *a*	....	110,200	6	7
1-inch gauge length . . . *b*	....	111,200	7	9
Average	....	110,700	6.5	8

These results show material of good ductility longitudinally and the stretch crosswise of the head shows up well for a transverse test.

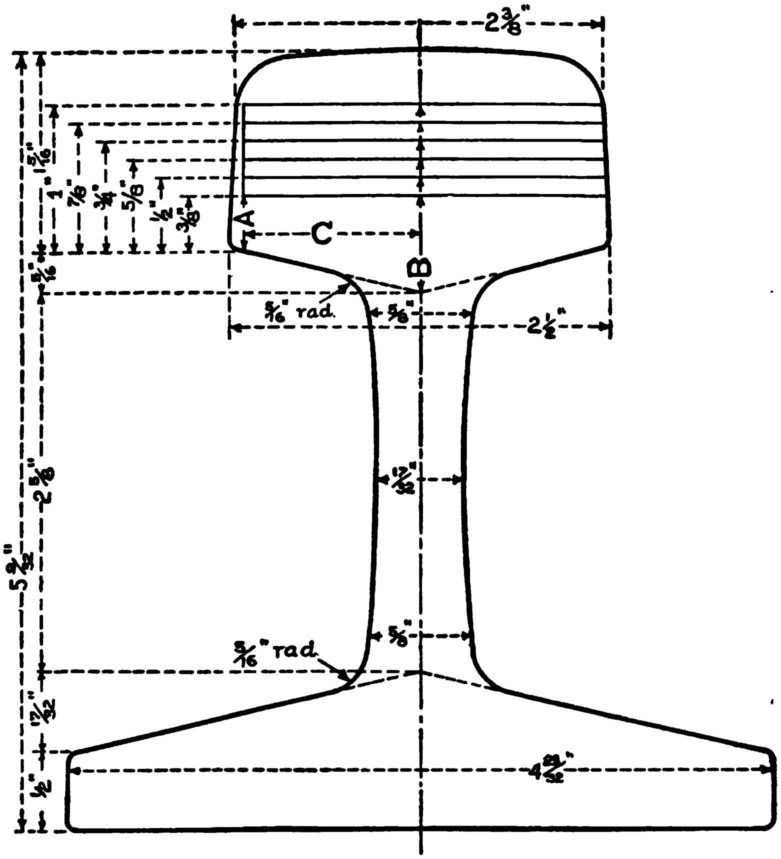


FIG. 177. — Diagram of Pieces tested for Sag of Rail Head and Bending of Web. (Am. Ry. Eng. Assn.)

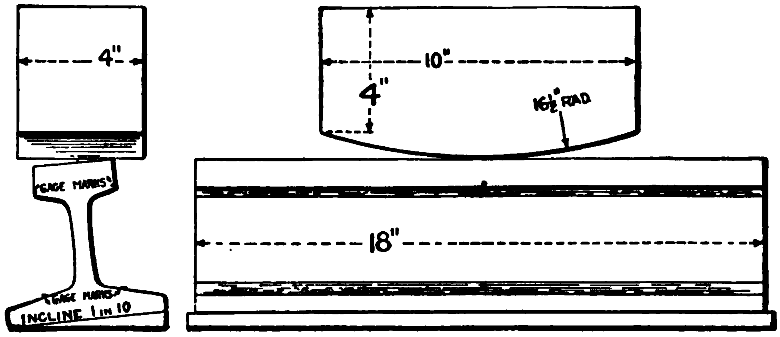


FIG. 178. — Method of Stationary Tests for Sag of Rail Head and Bending of Web. (Am. Ry. Eng. Assn.)

The arrangement used for making the stationary tests is shown in Fig. 178, and is intended to represent a 33-inch car wheel resting on the edge of the top of the rail. The head is thus tested as a cantilever, the load tending to sag the head locally and to also bend the web.

The load was applied in increments of 10,000 pounds up to 60,000 pounds and then in increments of 20,000 pounds up to 200,000 pounds, the capacity of the test machine. The sag of the head was determined by measuring the distance by means of dividers, between prick-punch marks placed on the side of the head near the bottom and on the base, as indicated in Fig. 178, the load being on while taking the reading. The marks on the base were placed about one inch from the web, by gouging some of the metal so as to have a vertical surface on which to prick-punch the mark. The amount that the opposite side of the head elevated, or the "lift," was determined in a similar manner. The results of these tests are shown in Table LXVI.

TABLE LXVI. — STATIONARY TESTS IN TEST MACHINE OF STRENGTH OF RAIL HEAD

Sag and Lift in Inches

Load.	$\frac{3}{8}$-inch Head.		$\frac{1}{2}$-inch Head.		$\frac{5}{8}$-inch Head.		$\frac{3}{4}$-inch Head.		$\frac{7}{8}$-inch Head.		1-inch Head.	
	Sag.	Lift.	Sag.	Lift.	Sag.	Lift.	Sag.	Lift.	Sag.	Lift.	Sag.	Lift.
10,000	.00	.00	.00	.00	.00	.00	.00	.01	......	......	.00	.00
20,000	.02	.00	.01	.00	.01	.00	.00	.01	.01	.02	.00	.00
30,000	.05	.00	.02	.01	.02	.00	.01	.01	.01	.02	.01	.00
40,000	.06	.01	.03	.01	.04	.00	.01	.02	.02	.02	.02	.01
50,000	.08	.01	.04	.01	.06	.01	.02	.02	.03	.03	.02	.01
60,000	.09	.02	.05	.02	.07	.01	.03	.02	.04	.03	.03	.02
80,000	......	......	.06	.02	.10	.02	.04	.03	.05	.04	.04	.02
100,000	......	......	.07	.02	.11	.03	.05	.03	.06	.04	.04	.02
120,000	......	......	.08	.02	.12	.03	.07	.03	.07	.04	.05	.03
140,000	.15	.03	.09	.02	.13	.03	.08	.03	.08	.04	.05	.03
160,000	.17	.03	.10	.02	.14	.04	.08	.03	.08	.04	.06	.03
180,000	.20	.05	.11	.02	.15	.04	.09	.03	.09	.04	.07	.03
200,000	......	......	.13	.02	.16	.04	.10	.03	.10	.03	.08	.02

These results are plotted in Fig. 179, in which the load is plotted against the sag of head for each thickness of head tested. The $\frac{5}{8}$-inch head, according to these curves, gave a greater sag than the $\frac{1}{2}$-inch head.

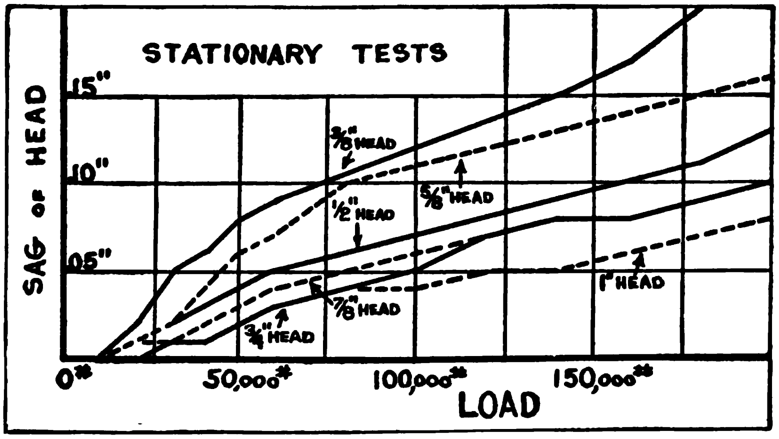


FIG. 179. — Sag of Rail Head in Stationary Tests. (Am. Ry. Eng. Assn.)

Although this is according to the measurements obtained, it would seem to be in error, due, perhaps, partly to errors of measurement, but probably also

due to some condition which cannot be accounted for, as, for instance, application of the load.

The curves show that a load of 10,000 pounds does not sag the head with the load applied to the edge of the top side, with any thickness down to $\frac{3}{8}$ inch, and probably neither does a load of 20,000 pounds, although, as the load was on when the measurement was taken, we cannot say how much of the sag was elastic and how much permanent. A load of 30,000 pounds seems to cause a permanent sag with the $\frac{3}{8}$-inch head, but not much, if any, with the heads of greater thickness.

It is interesting to note in this connection that the web seemed to stand the load of 200,000 pounds successfully.

Tests were also made with the reciprocating machine, shown in Fig. 151, in which a piece of rail is moved back and forth under a wheel to which a load can be applied by means of a system of levers. The rail is fastened to a steel bloom which runs on rollers running on another steel bloom that forms the bed of the machine. The rail bed is connected by means of a connecting rod to the bed plate of a planer, which furnished the power to run the rail machine. The weights attached to the weight hanger are multiplied 600 times as applied to the axle of the wheel, and in these tests weights of 50, 100, and 150 pounds were used, so that the wheel loads were 30,000, 60,000, and 90,000 pounds respectively. A piece of rail 18 inches long was tilted on an inclined plane of 1 in 10, as in the other tests, and the wheel, loaded with 30,000 pounds, was run back and forth over a length of about 10 inches for 100 double strokes, which made 200 movements of the loaded wheel over the rail. The sag of the head and the width of the bearing taken by the wheel were then measured with no load; the load was then increased to 60,000 pounds and the wheel again run on the rail as before. The measurements were again taken and a final test made with a load of 90,000 pounds. The results of these tests proved to be interesting and fairly definite, and are shown in Table LXVII.

TABLE LXVII. — RESULTS OF ROLLING TESTS OF STRENGTH OF RAIL HEAD

Thickness of Head.	Sag of Head. Inches.			Width of Bearing. Inches.		
	30,000 Pounds.	60,000 Pounds.	90,000 Pounds.	30,000 Pounds.	60,000 Pounds.	90,000 Pounds.
$\frac{3}{8}$ inch	.05	.13	.17	.56	1.20	1.56
$\frac{1}{2}$ inch	.01	.08	.13	.34	1.00	1.42
$\frac{5}{8}$ inch	.00	.05	.13	.31	.76	1.40
$\frac{3}{4}$ inch	.00	.03	.10	.32	.70	1.28
$\frac{7}{8}$ inch	.00	.01	.08	.32	.58	1.16
1 inch	.00	.00	.05	.23	.60	1.00

The results showing the relation of thickness of head and sag of head under loads of 30,000, 60,000, and 90,000 pounds are plotted in Fig. 180. It will be noted that 30,000 pounds produces no sag when the head is $\frac{5}{8}$ inch or over in thickness. With 60,000 pounds the head must be 1 inch or over in thickness. All the samples tested sagged under 90,000 pounds, but by extending the curve it seems probable that a head $1\frac{3}{8}$ inches thick would hold up a rolling load of 90,000 pounds when concentrated at the edge.

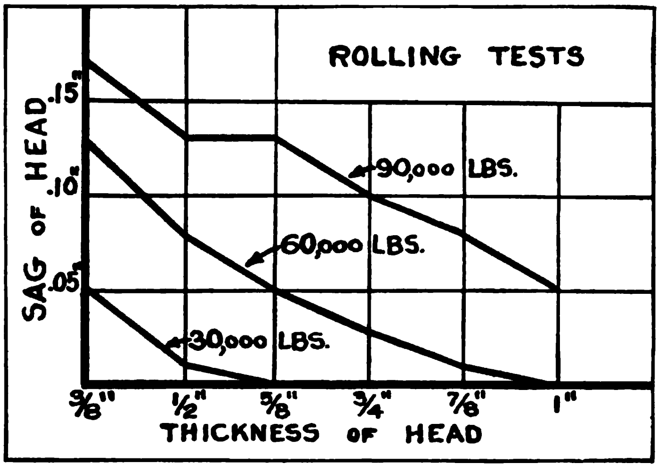


FIG. 180. — Sag of Rail Head in Rolling Tests. (Am. Ry. Eng. Assn.)

After the rails were tested they were cut in two and their sections are shown in comparison with the original rail section in Fig. 181.

The rolling load of 90,000 pounds applied at the edge of the head produced very little or no bending of the web with the section used, which was a 90-pound A. R. A. type B, with a thickness of about $\frac{9}{16}$ inch at the middle.

While there seems little liability of the web failing as a column, the height of the rail in reference to the stability of the outer rail on curves must be considered.

* Mr. E. E. Stetson found that in many cases the resultant of the horizontal force and wheel pressure on curves falls entirely outside the base of the rail in the 100-pound section.

In 1907 the Pennsylvania Railroad Company prepared a piece of track on the West Jersey and Seashore Railroad, on a 1-degree curve, near Franklinville, N. J., with special cast-steel ties and measuring apparatus, for the purpose of comparing the effects of lateral horizontal forces on the outer rail of the curve generated by different classes of electric locomotives and standard steam locomotives.

The force exerted by the locomotive was communicated to steel plates by means of hardened steel spheres of small diameter, and the effect of the force

* A Study of Rail Pressures and Stresses in Track Produced by Different Types of Steam Locomotives when Rounding Various Degree Curves at Different Speeds. E. E. Stetson, Proceedings Am. Ry. Eng. & M. of W. Assn., 1909, Vol. 10, Part 2, p. 1432.

was to cause the spheres to make a more or less deep impression in the steel plates.

By means of laboratory tests, it was determined what forces in pounds were required to produce various known depths of the impression of the steel balls in the plates, and after this calibration had been made it was possible to transform the depths of the impressions of the balls in the plates into pounds

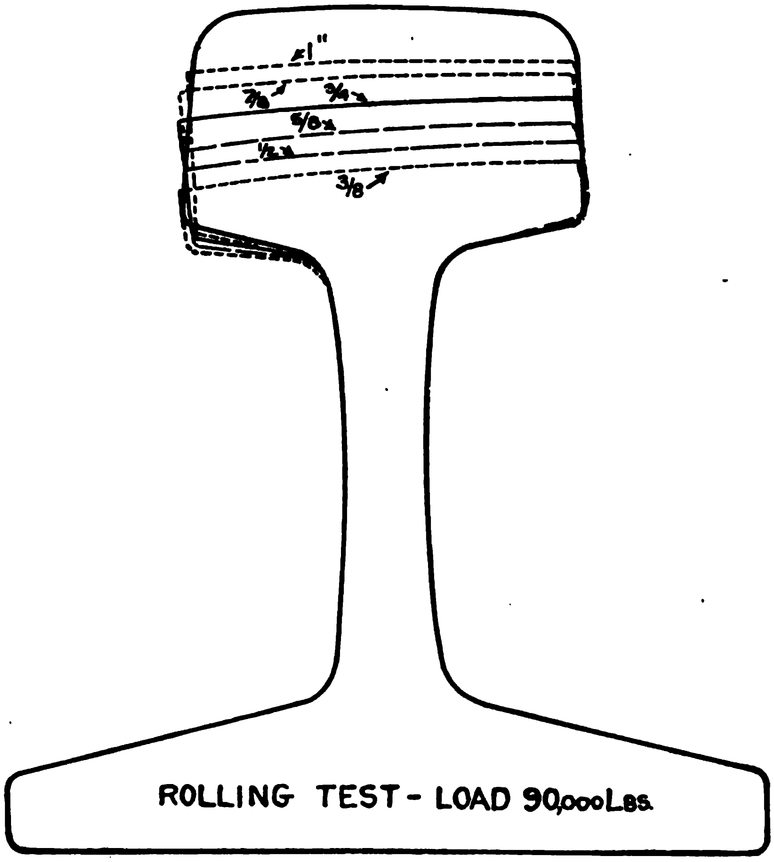


FIG. 181. — Rails after Rolling Test with Load of 90,000 Pounds. (Am. Ry. Eng. Assn.)

of pressure. Table LXVIII–A gives the results of some of these tests for steam locomotives, in order that they may be compared with the computations made by Mr. Stetson, which are shown in Table LXVIII–B for the same degree of curve and for one locomotive of the same class as used in the tests on the Atlantic City line. Mr. Stetson's calculations are for speeds of 60 miles per hour, which are from twenty to thirty miles per hour less than the actual tests, but the weights of the locomotives are heavier. The lower speeds should give smaller pressures, while, on the other hand, the heavier locomotives should give higher pressures.

TABLE LXVIII. — HORIZONTAL PRESSURES EXERTED BY STEAM LOCOMOTIVES AGAINST RAIL ON CURVES

(Am. Ry. Eng. Assn.)

TABLE A. — RESULTS OF TESTS MADE IN 1907, AT FRANKLINVILLE, N. J., ON WEST JERSEY & SEASHORE RAILROAD ON A 1-DEGREE CURVE

Run Number.	Speed in Miles per Hour.	Speed Corresponding to Superelevation.	Type of Locomotive.	Condition of Rail.	Maximum Depth of Impression.	Maximum Pressure in Pounds.
					Inch	
9	89.4	70	B	Dry	0.204	10,500
10	87.7	70	B	Dry	0.246	13,000
17	92.3	70	B	Dry	0.222	11,500
18	90.5	70	B	Dry	0.216	11,200
19	85.03	70	B	Dry	0.199	10,300
20	79.50	70	B	Dry	0.193	10,100
21	75.5	70	B	Wet	0.162	8,500
22	80.7	70	B	Wet	0.217	11,200
23	81.29	70	B	Wet	0.217	11,200
111	85.30	70	B	Dry	0.179	9,500
118	80.3	70	B	Wet	0.181	9,500
119	83.9	70	B	Wet	0.188	10,000
120	83.9	70	B	Wet	0.199	10,300
11	81.3	70	D	Dry	0.165	8,700
12	83.5	70	D	Dry	0.134	7,000

Class B is an Atlantic type locomotive, total weight = 176,600 pounds, height center of gravity above base = 73 inches.

Class D is an American type locomotive, total weight = 138,000 pounds, height center of gravity above base = 65 inches.

TABLE B. — RESULTS OF COMPUTATIONS MADE BY E. E. STETSON FOR A 1-DEGREE CURVE

Speed in Miles per Hour.	Speed Corresponding to Superelevation.	Type of Locomotive.	Pressure in Pounds.	Remarks.
60	60	Class B	11,500	Class B is an Atlantic type, total weight = 183,150 pounds, height center of gravity above rail taken as 70.5.
70	60	Class B	12,950	
60	60	Class A	11,120	Class A is Pacific type, total weight 270,100 pounds, height center of gravity above rail = 76.25.
70	60	Class A	12,830	
60	60	Class C	13,180	Class C is consolidation type, total weight 238,200 pounds, height center of gravity above rail = 62.
70	60	Class C	14,700	

24. Effect of the Joint

The preceding discussion is based on the assumption that the joint affords 100 per cent efficiency.

If we examine the functions the joint performs in carrying the load from one rail to the other, we see that the splice bars, by fitting tightly to the inclined surfaces of the head and base of the rail, are able by their friction to transmit large horizontal strains from one rail to the next. The proportion of the bending moment of the rail transmitted to the splice bar by this means is important in determining the correct proportions of the joint.

To determine the friction of the bar the following tests were made at the Watertown Arsenal in 1904.* There was first made a series of track observations on the Boston and Albany Railroad at Faneuil station, near Boston, to determine the resistance of nuts on bolts of splice bars as found in the track against further tightening.

Tests were made with a wrench 33 inches long, the resistance against tightening being shown by the force required at the end of the wrench to turn the nuts forward. The average of 60 observations was 52 pounds on a 33-inch wrench.

Tests were then made at the Arsenal on the frictional resistance of two 6-hole splice bars on two sections of 6-inch 100-pound rail. Spring nuts were used under the nuts, ¾-inch bolts, 10 threads per inch, length of wrench used 33 inches. The results of the tests are shown in Table LXIX.

TABLE LXIX. — FRICTIONAL RESISTANCE OF SPLICE BARS

(Watertown Arsenal)

Tightening Force Applied to Wrench (Pounds).	Frictional Resistance of Joint.	
	Initial (Pounds).	Continuous Movement (Pounds).
50	37,500	33,800
75	46,900	44,700
85 — 5 bolts	72,800	65,500
110 — 1 bolt	72,800	65,500
50	31,000	28,600

The maximum pull applied to five of the bolts in the third test, 85 pounds on a 33-inch wrench, was the limit of strength of the bolts. This pull on the wrench caused a permanent elongation of about .06 inch to .10 inch on each of the five bolts. The sixth bolt resisted a pull of 110 pounds on the wrench without material elongation.

After making observations on the frictional resistance in these tests, the first test, with bolts tightened to 50 pounds' pull, was repeated.

The splice bars were now used on one piece of rail, using four bolts, the nuts of which were tightened with a pull of 50 pounds on a 33-inch wrench. The initial resistance was 50,900 pounds and movement continued under 31,200 pounds.

Tests with four bolts in one piece of rail, with 50 pounds' pull on the wrench, were repeated with an initial resistance of 59,200 pounds. The movement continued under 41,600 pounds.

* House Documents, Vol. 78, No. 291, 58th Congress, 3rd Session, 1904–05, Tests of Metals.

The tension on the bolts was reduced during test, and after the last observations were made the nuts could be further tightened with a pull of 30 pounds. Each nut could be turned up 90 degrees before again attaining a resistance of 50 pounds on the wrench.

One-half joint was again made up with four bolts and 50 pounds' pull on the wrench. The initial resistance was 66,500 pounds. The slipping of the angle bars occurred with a series of throbs, immediately followed in each instance by a reduction in the load on the bars. The succeeding throbs took place under gradually diminishing loads, following to 49,300 pounds at the fourth throb. When removed from the testing machine, the nuts could be turned on with an average pull of 35 pounds on the wrench.

* The experiments carried out by Messrs. Résal, Poutzen, and Ménard on the longitudinal slipping of rails connected by fishplates were of four descriptions, viz.:

(1) On new rails with new fishplates and bolt holes;
(2) On the same rails lubricated with mineral oil;
(3) On old rails with worn bolt holes; and
(4) On the same with the addition of a thin layer of sand between the surfaces of contact.

It was found that the old rails gave the best results and required a pressure of 18 tons to effect any appreciable movement, whereas the new rails were least satisfactory, particularly after oiling. As to the experiment with sand, it was found that, owing to the reduction of the surfaces of contact caused by the sand, the slipping was about the same as in the case of new rails.

Dr. P. H. Dudley found that a well-fitted splice bar for a 5-inch rail required over 4000 pounds per linear inch of one-half of the length of the bar to overcome the friction in the rail ends, and for 90-pound and 100-pound 6-inch rail, 4500 and 4800 pounds respectively

We are probably not warranted in taking the frictional resistance of the joint at more than 40,000 pounds; nor can the friction between the rail and the splice bar be well increased by the use of special joints, without at the same time increasing to an undesirable extent the stresses in the rail, caused by sudden changes in temperature.

It will be seen that this frictional resistance may cause an initial tensile stress of about 4000 pounds per square inch in the 100-pound rail at times of a sudden fall in temperature.

* Revue Générale des Chemins de Fer, Paris, 1908, Vol. 31, pp. 8–14.

The tension set up in rails of lighter section in falling temperatures, before they render in the splice bars, is considered by Dr. P. H. Dudley to be important and indirectly responsible for a large number of the cracked or broken rails which occur during falling temperatures. Records and dates of broken rails taken by Dr. Dudley for a number of years, when compared with the dates of decided falling temperatures, were found to practically coincide, but as soon as the temperature would rise, relieving the rails from tension or putting them in compression, the breakages would cease, except in cases of a development of a check which commenced in a falling temperature.

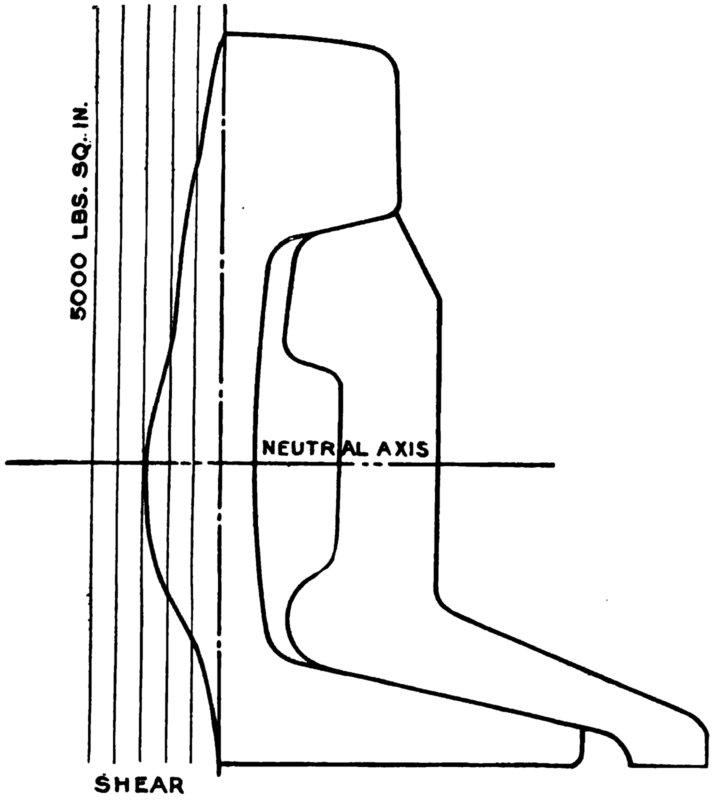


FIG. 182. — Shearing Stress in 100-pound A. S. C. E. Rail and Splice Bar. Total Shear, 24,000 Pounds.

If we consider the effect of the frictional resistance between the splice bar and the rail, it is apparent that the bar shown in Fig. 182 will act as an integral part of the rail until the longitudinal shear at the surfaces of contact of the rail and the bar exceeds the resistance caused by friction on these surfaces. This resistance for a 20-inch splice bar may be taken as 4000 pounds per linear inch for the entire joint, or 1400 pounds per square inch for

the upper surface of contact, and 500 pounds per square inch for the lower surface of contact.

It is seen from the figure that the surface friction is sufficient to carry a total shear at the section of 24,000 pounds, and by referring to the rail diagrams given in Figs. 171 and 172 it would appear that the maximum bending moment in the rail would be transmitted to the splice bars without slipping. However, between the two rails the splice bars must carry the entire moment, and unless the section of the bar is increased at the middle of the joint there results an excessive deflection at this point.

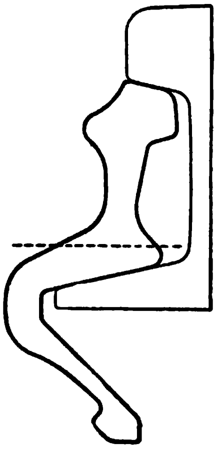


FIG. 183. — 100 per cent Joint.

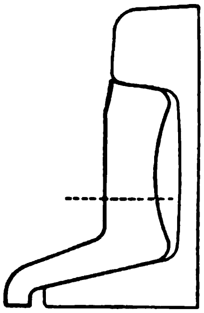


FIG. 184. — Joint showing Uneconomical Distribution of Metal.

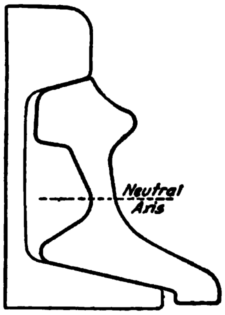


FIG. 185. — Joint showing Economical Distribution of Metal.

To overcome this source of weakness in the joint, the form shown in Fig. 183 has been found to embody most of the essential elements demanded by the extra reinforcement needed at the center of the joint. This section is only used at the middle of the bar and the section shown in Fig. 185 is used for the rest of the bar.

It will be seen that the added metal is distributed in such a way as to still keep the vertical axis within the vertical surface that is gripped by the bolts. The sectional area and moment of inertia of the reinforcement shown in Fig. 183 can readily be adjusted to match the stiffness of the rail that is to be spliced, whereas, with the space limitations of Fig. 185, it is not possible to get a higher relative percentage of strength than, say, 40, as compared with the rail.

The splice bars, shown in Figs. 184 and 185, show the greater stiffness that can be obtained by means of a proper distribution of the metal. Taking the

stiffness of the rail as 100 per cent, the relative stiffness of the bars, shown in Figs. 184 and 185, is 29.1 per cent and 37.3 per cent respectively.*

As far back as 1876 quite full experiments were made with a modified type of reinforcement shown in Fig. E, Plate XXIV, on the Swedish Government Railroads, and in the German handbooks of somewhat later dates quite a variety of sections are found of this same general shape. The reinforcing vertical flange occupied a plane at some distance from the axis of the rail, which causes the vertical axis of the splice bar to assume a position outside the vertical surface that is gripped by the bolts, and in consequence the resisting stresses in the flange itself must cause an outwardly rotating action, tending to strip the threads of the bolts.

Plate XXIV shows types of joints used in this country. † Fig. A on this plate illustrates the common type of angle bar. The variations from this section, as applied to 80- and 85-pound rail, are in many directions. A comparatively frequent one is the thickening of the vertical web to $\frac{7}{8}$ inch. Another tendency is to put more metal into the upper part of the web near the under side of the rail head. An extreme development of this latter practice is shown in the Pennsylvania's angle bar for use with its new section of rail. Fig. B shows this section. The horizontal extension of the lower flange of the bar is another direction in which the angle-bar section is frequently modified.

There are six patented joints which are now in service in sufficient numbers to merit consideration. They may be divided into two classes: those with deep girder flanges, namely, the Hundred per cent, the Duquesne, and the Bonzano, Figs. C, D, and E; and those which are base-supporting, as the Continuous, the Weber, and the Wolhaupter, Figs. F, G, and H.

The Rail Committee of the American Railway Engineering Association have recently made a series of interesting tests on rail joints at the Watertown Arsenal.‡

(1) Three joints of each kind were furnished, of which two were used for testing and the third joint was reserved for future use if needed.

(2) All joints were full-bolted. Several of the joints first tested had various sized openings between the rail ends. After the test of the first three joints, all other joints were changed so that the opening between the ends of the rails was as close to three-eighths of an inch as possible. The span between supports in the testing machine was 30 inches.

* Railroad Age Gazette, April 9, 1909, p. 804.

† Railroad Age Gazette, March 19, 1909.

‡ Bulletin No. 123, May, 1910, Am. Ry. Eng. & M. of W. Assn.

(3) One joint was tested with the load first applied to the base, in increments of 2000 pounds, until the limit of 32,000 pounds was reached, and then the joint was reversed and the load applied on the head until the joint failed or the limit of the machine was reached.

(4) The second joint was tested by first applying the load on the head and then reversing it, applying the load on the base, until the limit was reached.

(5) With the exception of the joints furnished by the Cambria Steel Company and Mr. A. Morrison, the joints were selected from material which had

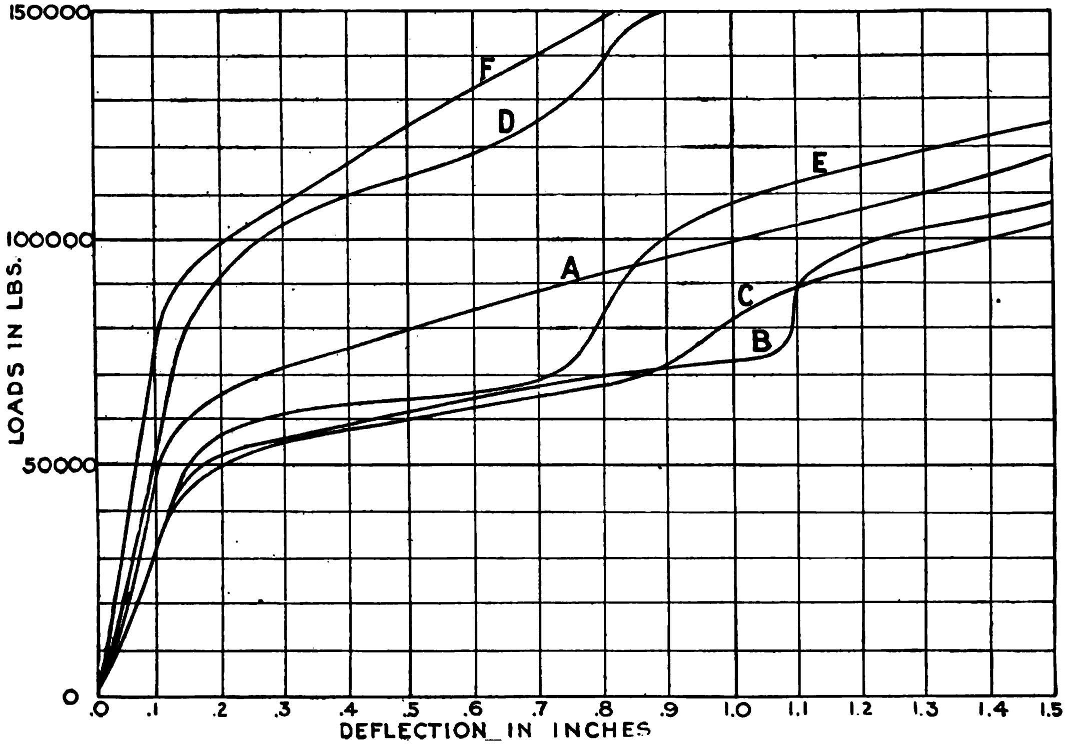


FIG. 186. — Diagram of Watertown Arsenal Tests on 100-pound Joints. (Am. Ry. Eng. Assn.)

been furnished by the manufacturers to the railroad companies in the regular routine of business, and therefore fairly represent the material ordinarily furnished by the manufacturers.

Figs. A to F (Plate XXV) show some of the joints tested; the results of the tests on these joints are presented in Fig. 186. The material in the different splice bars varies so widely that it is difficult to judge of the value of the different designs. The excellent results obtained with the Dudley joint (Fig. D) is probably due to the high strength of the metal as compared to the other joints tested.

The rolling mills are reluctant to make splices of higher carbon, Bessemer process, than .10 to .20 per cent. Some railroads have specified as high as .63 per cent, and with good results both as to manufacture and experience. The mill, however, suffers by such a high standard. One mill claims to have broken one-third of the total quantity of bars in the straightening process, and it also broke many of the punches.

Splices made from steel of .50 carbon appear to give much better results, as might be expected, than the softer steel bars. It is necessary to hot-punch the higher carbon steel, and when this is done there is no difficulty in properly manufacturing them. The Cambria Steel Company are rolling bars of this grade of steel which are hot finished and oil tempered.

* The economic advantage of high-carbon steel, hot finished, is that, with the expenditure of about 10 per cent more than the cost of soft steel, a joint is given a carrying capacity that can be equaled only by the addition of double the quantity of metal of soft steel and at the additional cost of 100 per cent. This latter joint will cost 100 per cent more for freight, while there is no additional cost for freight in the former.

The oil treatment of steel is a natural sequence of the use of high carbon, and its advantages are about equal to those of high carbon over soft steel. This, however, varies with the section of the bar and hardness of the steel. In economy, oil-treated steel is as much in advance of high-carbon steel as is the latter over soft steel.

Intimately connected with the rail-joint problem is the question of the length of the rail. In a recent bulletin (August, 1909) of the International Railway Congress, the practice in English-speaking countries is very fully discussed and abstracts from this report are given below.

In Great Britain and Ireland the railways have been gradually increasing the length of rails, with a view to reducing the number of joints. Some railways still use rails only 30 feet long, and a few use 60-foot rails, but a large number have 45-foot rails, and it appears that this may be taken as a standard for the near future. The principal reasons given for limiting the length, as given by the engineers of different railways, may be summarized as follows: (1) Difficulty of straightening rails at the mills; (2) cost of manufacture; (3) difficulties of transportation; (4) expansion and contraction; (5) unloading and handling on the track.

So far the use of long rails does not appear to have called for the adoption of any special arrangements other than proper proportioning

* Railway Age Gazette, March 16, 1910, daily edition.

of the bolt holes and the play at the joints, and the strengthening of the maintenance gangs (by consolidating neighboring gangs or otherwise) while handling long rails. The temperature varies from 0° F. in winter to a maximum of 130° F. in the sun in summer. To allow free play for expansion during extreme heat, it is the practice of most engineers to ease the joints by slackening the nuts.

In the United States the standard length on a number of railways is 33 feet, and the reasons given for limiting the length are, in general, similar to those noted above. Experiments have been made with rails of greater length, but on the whole these have not been satisfactory, although the opinions expressed by some of the railways give 40 feet, 45 feet, 50 feet, and 60 feet as admissible lengths. The range of temperature is 100° F. in some parts of the country, while in others it is 180° F. In some cases the nuts are slackened in the early part of the summer.

In the roads of other countries investigated which include 17 railways in South America, India, South Africa, Australia, and Canada, the limiting length of rails varies from 30 to 40 feet. The range of temperature is from 100° to 155° in India, and 160° in South Africa and Australia.

Inquiry was made as to whether any railways contemplated welding the rails at the joints. All the replies were in the negative, and the general opinion was that continuous rails would be unsafe, on account of the temperature changes. It is well known, of course, that welding the joint is common practice in street railway work, but in such cases the rails are protected by the paving, so that only a small portion is exposed.

The following very interesting report from the Pennsylvania Lines is quoted in the bulletin:

"In 1897 a continuous rail, 1050 feet long, made up of 35 80-pound 30-foot rails joined by angle bars with drilled holes and machine-turned bolts (no provision being made for expansion and contraction), was laid in the eastbound main track, near New Brighton, Pa. The ends were held by bent rails bedded in concrete, so placed as to bear against the ties. Special long and wide angle bars were used at the ends, fastened to the anchor ties with lag screws. The track was a tangent with stone ballast.

"The rail crept and kinked out of line badly. An examination made in August, 1900, after three years' service, showed that the entire rail crept in the direction of traffic (eastward). At the west anchorage, the vertical holding rails had cut into the cross-ties forming the anchorage framework, while at the east anchorage there was a space of $1\frac{3}{4}$ inches between the vertical rails and the

framework. All of the spikes were bent eastward, and both slots and spikes were badly cut. The bolts were all slightly sprung. The alignment at the joints was very bad." *

The conclusions presented in the bulletin are given below: In Great Britain and Ireland, the lengthening of rails and the consequent reduction of the number of joints has been steadily proceeding at an increasing rate during the past 60 years. In 1840–50, the normal length of rolled iron rails was from 15 to 18 feet. The length of these iron rails increased at the rate of about 3 feet in each decade until 1870–80, when steel rails from 24 to 30 feet long were brought into general use. Since then the decennial increase has been about $4\frac{1}{2}$ feet, and at the present time rails 36 feet and 45 feet long are in general use, while two railways have adopted 60 feet in length.

In 1904, when the Engineering Standards Committee issued the British Standard sections, it recommended the adoption of the following as the normal lengths of rails: 30, 36, 45, or 60 feet. In other countries embraced by the report, the length of rails has been steadily and uninterruptedly increasing, but within narrower limits than in Great Britain and Ireland.

The conclusions to be drawn from the numerous replies and remarks by engineers throughout the English-speaking countries are that there is a maximum length of rail somewhere between 33 feet and 60 feet, which should not be exceeded; and continuous or welded joints over a long length of railway are impracticable and dangerous.

BIBLIOGRAPHY

Blum. — Report . . . on the question of rail joints. (All countries except France, Belgium, Italy, Spain, Portugal, Austria-Hungary, Rumania, Bulgaria, Servia, Turkey, Egypt, and countries using the English language.) 48 p. Ill. 1910. (In Bulletin of the International Railway Congress, Vol. 24, Part 1, p. 1701.)

Bouchard, H. — Note sur le joint asymétrique. 4000 w. Ill. 1909. (In Revue générale des chemins de fer, Vol. 32, p. 9.)

Describes theory, construction, and results with favorable rail joint.

Chateau. — Report . . . on the question of rail joints (France, Belgium, Italy, Spain, and

* The author several years ago had experience with a continuous rail designed by the late Mr. Torrey.

The rail was about the length and of the same weight as in the Pennsylvania test. It was laid on a branch line of the Michigan Central Railroad on a tangent and ballasted with a good bed of gravel. Provision was made at intervals of about 500 feet throughout the test track for the expansion of the continuous rail by means of special expansion joints, the rail being anchored midway between these joints.

When first installed the riding qualities of the track were exceptionally good, which may, however, have been accounted for by the unusual care that had been taken in constructing it. After several years the test track appeared to ride about as well and to require the same amount of attention as the other track on the division.

Portugal). 38 p. Ill. 1910. (In Bulletin of the International Railway Congress, Vol. 24, Part 1, p. 1427.)

EDELSTEIN, LEON. — Prevention of play between rail and fishplate. 2000 w. Ill. 1908. (In Bulletin of the International Railway Congress, Vol. 22, Part 1, p. 436.)

Shows faults that develop with wear, and gives suggestions for prolonging life of both rails and fishplates.

GODFERNAUX, R. — Note about rail-joints. 24 p. Ill. 1911. (In Bulletin of the International Railway Congress, Vol. 25, p. 1480.)

Reviews development of rail joints and different forms used.

HAARMANN, A. — Der schienenstoss. 5000 w. Ill. 1911. (In Stahl und eisen, Vol. 31, Part 1, p. 49.)

Discusses types of rail joints and probable future practice in track construction.

Improvements and experiments in rail joints. 2500 w. 1910. (In Engineering News, Vol. 64, p. 281.)

Abstracts information from reports to International Railway Congress on practice in the United States, Great Britain, France, Belgium, and Austria-Hungary.

INTERNATIONAL RAILWAY CONGRESS. — [General discussion on rail joints.] 38 p. 1911. (In Bulletin of the International Railway Congress, Vol. 25, p. 405.)

KRAMER, FRIEDRICH. — Report . . . on the question of rail-joints (Austria, Hungary, Rumania, Bulgaria, Servia, Turkey, and Egypt). 82 p. Ill. 1910. (In Bulletin of the International Railway Congress, Vol. 24, Part 1, p. 1967.)

JONES, CYRIL WALTER LLOYD. — Design of fishplate rail joints. 7000 w. Ill. 1910. (In Minutes of Proceedings of the Institution of Civil Engineers, Vol. 182, p. 282.)

PELLARIN. — Étude des joints des rails. 27 p. Ill. 1908. (In Annales des ponts et chaussées, Mémoirés, series 8, Vol. 33, p. 98.)

Report of commission for investigation of rail joints in Belgium, Italy, Switzerland, and Holland.

ROSS, ALEXANDER. — Report . . . on the question of rail joints. (Countries using the English language.) 44 p. Ill. 1909. (In Bulletin of the International Railway Congress, Vol. 23, Part 2, p. 689.)

CHAPTER V

STRENGTH OF THE RAIL

25. Influence of Stress and Strain on the Strength of the Rail

In determining the safety of any structure, not only the amount of stress induced in the different members by the load must be found, but its character and the effect it may produce on the material of which the structure is composed must be considered.

A series of rapidly repeated stresses will, under certain conditions, affect the breaking strength of the metal. The cause of this loss of strength under the influence of repeated stress is a much-mooted question among engineers, and it is of interest to examine the problem in detail.*

Fig. 187. — Pure Swedish Iron. (Mellor.) Fig. 188. — Pure Copper. (Arnold.)

The junction of the crystalline grains of pure iron, shown in Fig. 187, and of pure copper, shown in Fig. 188, are typical of pure metals; but when impurities are present the crystals of the pure metal, in the act of crystallizing, reject the impurities which collect at the crystal boundaries. The particles of pure metal slowly migrate and coalesce together, so as to form little islands surrounded by the impurity; accordingly, in the solidified mass, we find the crystals of pure metal enveloped by a film of the metal associated with the foreign sub-

* The author is indebted for the discussion on pp. 270–276 to Mr. J. W. Mellor's work, The Crystallization of Iron and Steel, Longmans, Green & Co., London, 1905.

stance. This investing membrane separates the crystals of pure metal one from the other. Obviously, the mechanical and physical properties of the alloy will depend upon the character of the film.

The mass of pure metal, for example, may be quite ductile like gold, while the mass of metal with the impurity may be quite brittle, as Arnold * found to be the case with an alloy of gold with .2 per cent of bismuth; and copper containing .5 per cent bismuth. A representation of the latter alloy is shown in Fig. 189. When such a metal is fractured, the line of fracture follows the junction of the grains.

Stead calls this ailment intergranular or intercrystalline weakness (*inter*, between). We have had examples. Arnold's work on the influence of bismuth

FIG. 189. — Copper-bismuth Alloy. (Arnold.)

FIG. 190. — Iron with 1.8 per cent Carbon. (F. Popplewell.)

on copper and on gold. One per cent of sulphur arranged as a mesh of iron sulphide will entirely destroy the ductility of the iron, reducing the ultimate stress from 20 to 2 tons per square inch.

The network of cementite which envelops the crystal grains of steel containing over 1 per cent of carbon are the principal lines of weakness. The metal when fractured generally breaks through the center of this brittle envelope. The coefficient of contraction of the cementite cell walls is greater than of the cell contents. Pearlite cells, for example, bound together by thick cementite walls (Fig. 190), are liable to rupture, because the coefficient of contraction of the cementite cell walls is greater than the cell contents. The mass is, in consequence, very feebly held together, and a sudden blow will easily fracture the metal.†

* J. O. Arnold and J. Jefferson, Engineering, 61, 177, 1896.
† J. O. Arnold, Metallographist, 5, 267, 1902.

Intergranular weakness resembles the weakness of a brick building with faulty mortar.

There is another type of intergranular weakness which is due to imperfect union of the crystal grains. This is particularly marked in phosphorous steels. The crystal grains, on cooling, contract unequally and tend either to draw the grains away from each other or to leave the mass in a state of unnatural tension. The fracture then follows the granular junctions. Thick plates and bars are frequently brittle because comparatively little work has been done on them. The crystals are not interlocked one with another, as in steel which has been well worked.

Intergranular weakness may, therefore, be of two kinds:

(1) Brittle envelope surrounding the crystal grains;

(2) Imperfect union of the crystal grains.

Stead has pointed out another type of weakness in sheet steels which has to do with the crystals themselves, without reference to the union of one crystal with another. It is a kind of intracrystalline weakness (*intra*, within).

It is characteristic of some crystals to break more readily in some directions more than in others. This property of crystals is called cleavage. The directions in which the crystal splits are called cleavage planes. If a bar of iron could be cut from a single crystal, that bar would have three lines of weakness in the direction of the three cleavage planes; while if the bar were built up of a number of crystals whose cleavage planes were all in the same direction, that bar would be more readily broken in the direction of its cleavage planes, neglecting for the moment intergranular weakness. On the other hand, if the cleavage planes of the adjacent crystals are inclined at considerable angles to one another the bar would be less liable to break than one in which the crystals were arranged symmetrically. Figs. 191 and 192 will make this clear. The dotted lines *ab*, Fig. 191, represent the cleavage planes across a sheet of iron when the crystals are arranged symmetrically, while in Fig. 192 the crystals are arranged in an irregular manner. The cleavage planes of Fig. 191 run along parallel lines, and the sheet would, therefore, be more liable to rupture than the sheet shown in Fig. 192, where the lines of weakness are not in the same direction, and this in spite of the fact that Fig. 191 has a finer grain.

Other things being equal, a fine-grained structure is stronger and tougher than a coarse-grained piece. Figs. 191 and 192 show that this order of things may be reversed. Fortunately, the crystals of one steel do not generally grow symmetrically.

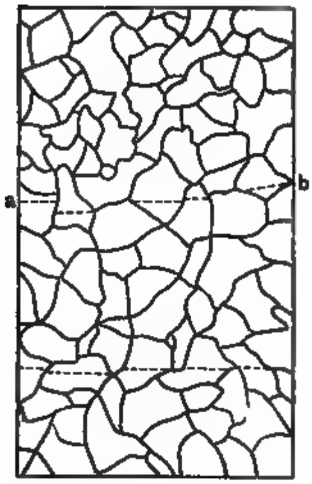


FIG. 191. — Cleavage Planes with Crystals arranged Symmetrically. (J. W. Mellor.)

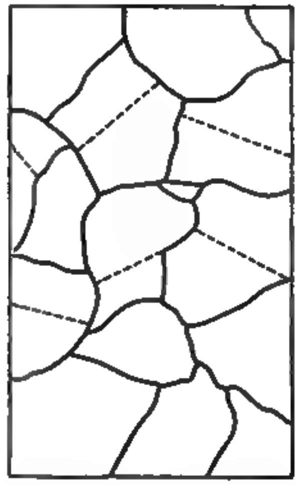


FIG. 192. — Cleavage Planes with Crystals arranged in an Irregular Manner. (J. W. Mellor.)

FIG. 193. — Iron strained beyond the Elastic Limit. (J. A. Ewing and W. Rosenhain.)

FIG. 194. — Lead strained beyond the Elastic Limit. (J. A. Ewing and W. Rosenhain.)

Examining now what takes place in the metal under repeated stress, Ewing and Rosenhain * found if a metal is strained past its " yielding point " — elastic limit — the faces of the crystal grains (Fig. 193) show fine black lines, which increase in number as the strain increases. Lines appear on certain crystals nearly transverse to the pull, as the strain increases lines appear upon other

* J. A. Ewing and W. Rosenhain, Phil. Trans., 193, 353, 1899; 195, 279, 1900. J. A. Ewing and J. C. W. Humfrey, Ibid , 200, 241, 1902. W. Rosenhain, Journal Iron and Steel Inst., 67, i, 335, 1904. F. Osmond and C. Frémont and G. Cartaud, Revue de Métallurgie, 1, i, 1904.

grains. Intersecting lines then make their appearance on some of the grains. Such a strained surface is shown in Fig. 194.

The lines are apparently not actual cracks in the surface, but rather slips along the cleavage planes of the crystal. They are called slip bands, or slip lines.

Let AB (Fig. 195) represent a cross section through a polished surface of metal. Let C be the junction between two contiguous grains, A and B. When the metal is pulled in the direction of the arrows, a number of slips are developed along the cleavage planes, a, b, c, d . . . , and the surface now presents

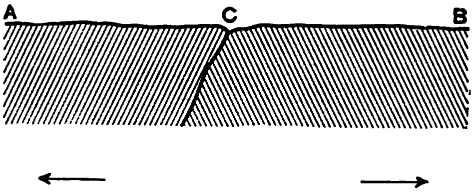


FIG. 195. — Cross Section of Unstrained Metal. (J. W. Mellor.)

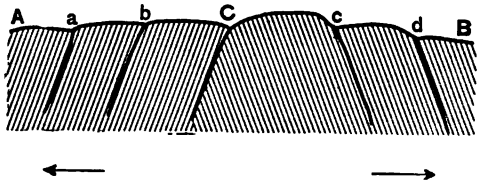


FIG. 196. — Cross Section of Metal after being Stressed. (J. W. Mellor.)

the appearance shown in Fig. 196. With still greater strains the slip bands develop into actual cracks, and rupture takes place. Hence it follows that under progressively augmented strain, rupture takes place, not at the crystal boundaries, but through the crystals themselves.

Ewing and Humfrey have subjected Swedish iron, with a breaking stress of 23.6 tons per square inch, to a series of compression and tension stresses, 9 tons in magnitude, repeated 400 times per minute. On examination it was found that fine slip bands appeared in a few crystals after a few, say, 5000 reversals of stress; with a greater number, say, 40,000, the slip bands increase in number, and those which first appeared broaden and develop into small cracks, as shown in Fig. 197.

If the specimen be repolished, so as to clear off the slip bands, the cracks alone become visible, as at A (Fig. 198). The crack, or flaw, gradually creeps across the specimen when the number of alternations is still further increased, as shown in Fig. 199. Finally the specimen breaks.

Ewing and Humfrey state: " Whatever the selective action of the stress is due to, the experiments demonstrate that in repeated reversals of stress certain crystals are attacked, and yield by slipping, as in other cases of non-elastic strain. Then, as the reversals proceed, the surfaces upon which the slipping has occurred continue to be surfaces of weakness. The parts of the crystal lying on the two sides of each such surface continue to slide back and forth over one another.

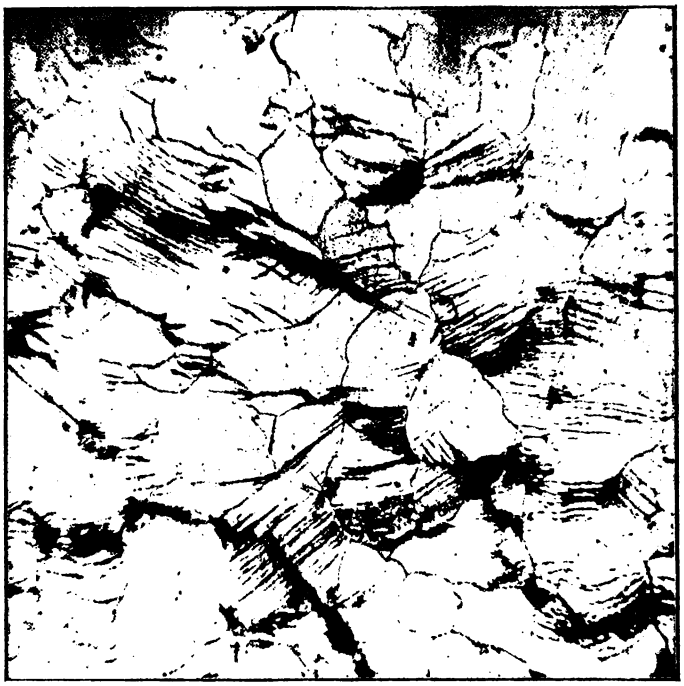


FIG. 197. — Slip Bands. (J. W. Ewing and J. C. W. Humfrey.)

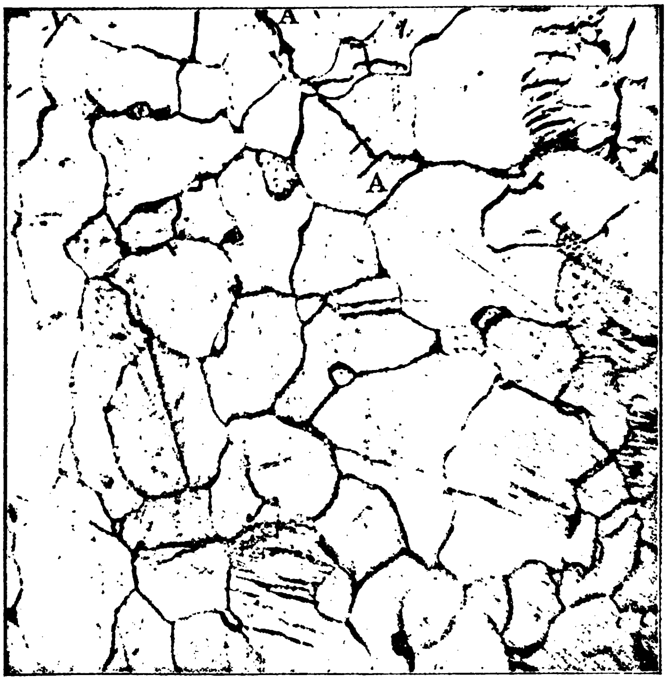


FIG. 198. — Polished Surface with Small Cracks. (J. W. Ewing and J. C. W. Humfrey.)

"The effect of this repeated sliding or grinding is seen at the polished surface of the specimen by the production of a burr or rough and jagged irregular edge, broadening the slip band, and suggesting the accumulation of débris. Within the crystal this repeated grinding tends to destroy the cohesion of the metal across the surface of the slip, and in certain cases this develops into a crack.

"Once the crack is formed, it quickly grows in a well-known manner, by tearing at the edges, in consequence of the concentration of stress which

FIG. 199. — Polished Surface with Large Cracks. (J. W. Ewing and J. C. W. Humfrey.)

results from lack of continuity. The experiments throw light on the known fact that fracture by repeated reversals or alternations of stress resembles fracture resulting from 'creeping flaw' in its abruptness, and in the absence of local drawing out, or other deformation of shape." *

The rupture of steel is not caused by the gradual growth of the crystalline structure of the metal under the influence of shocks and vibrations. The breaking down is due to fatigue. When fatigued, the metal breaks more readily. Again, when subjected to sudden shock, the metal has no time to "flow." The

* P. Kreuzpointer, Journ. Franklin Inst., 153, 233, 1902. J. A. Ewing, Nature, 70, 187, 1904. P. Breuil, Suppl. Journ. I. & S. Inst., 1904.

slipping of the crystal planes, or the plasticity of the metal, has no time to come into play. The metal, in consequence, appears to be abnormally brittle.

* The experiments made by Wöhler, from 1859 to 1870, were the first that indicated the laws which govern the rupture of metals under repeated application of stress. For instance, he found that the rupture of a bar of wrought iron by tension was caused in the following ways:

By 800 applications of 52,800 pounds per square inch.
By 107,000 applications of 48,400 pounds per square inch.
By 450,000 applications of 39,000 pounds per square inch.
By 10,140,000 applications of 35,000 pounds per square inch.

Here it is seen that the breaking unit stress decreases as the number of applications increases. It was further observed that a bar could be strained from 0 up to a stress near its elastic limit an enormous number of times without rupture, and it was also found that a bar could be ruptured by a stress less than its elastic limit under a large number of repetitions of stress which alternated from tension to compression and back again.

† The apparatus used by Wöhler and his successor, Spangenberg,‡ was of four kinds:

(1) To produce rupture by repeated load;
(2) For repeated bending, in one direction, of prismatic rods;
(3) For experiments on loaded rods under constant bending stress;
(4) For torsion by repeated stress.

The amount of the imposed stress was determined by breaking several rods of like material, ascertaining the breaking load, and taking some fraction of this for the intermittent load.

From the results of these experiments of Wöhler, extending over eleven years, the following law was deduced:

"Wöhler's Law: Rupture of material may be caused by repeated vibrations, none of which attain the absolute breaking limit. The differences of the limiting strains are sufficient for the rupture of the material."

The work of Wöhler and Spangenberg has proved what was long before supposed to be the fact: that the permanence and safety of any iron or steel structure depends not simply on the greatest magnitude of the load to be sustained, but on the frequency of its application and the range of variation of its amount.

* A. Wöhler, Engineering, 1871; Zeitschrift für Bouwesen, 1870, p. 83, Berlin.
† Iron and Steel, Materials of Engineering, Part 2, Thurston, 1909, p. 618.
‡ Zeitschrift für Bouwesen, 1874, p. 485, Berlin.

Prof. L. Spangenberg resumed the line of experiments at the point of its discontinuance by Wöhler, and his results tend to confirm the law of the latter. Spangenberg directed his attention to other metals than iron and steel, and also endeavored, by inspection of the surfaces of fracture, and by his hypothesis as to the molecular constitution of metals, to explain the phenomena of fracture. Among the several observations noted in his "Fatigue of Metals" is the important fact that when subjected to often-repeated transverse stress fracture of iron took place only on the tension side of the bar and extended only to the neutral axis. From this he inferred that the working strength of wrought iron is less than its elastic resistance.

Fowler states, in this connection, that a steel rail tested for transverse strength in a machine will, as a rule, bend many inches, and fail by distortion of the head under the compressive stress. In actual work hundreds of such rails break, but it is the tensile and not the compressive stress which causes the failure, and there is no distortion of the head, as in the testing machine.

Reynolds and Smith * extended Wöhler's conclusions to steel bars tested under direct tension and compression and at a rapid rate of alternation. The work of Stanton and Bairstow,† published in 1906, while less concordant than that of Reynolds and Smith, confirms their general conclusions; it extends the conclusions of Ewing and Humfrey to notched specimens tested for endurance under direct tension and compression, and it clearly points out the advisability of testing a material for endurance in approximately the form in which it is to be used in practice.

French engineers, commenting upon the work of Wöhler, Spangenberg, Weyrauch,‡ and Launhardt, consider that the result is simply to base upon the ultimate strength a deduced limit of working stress which corresponds closely to the elastic limit, and generally urge the use of a reasonable factor of safety related to the limit of elasticity.§

Figs. 200, 201, and 202 present three diagrams on the behavior of steels under repeated alternate stresses, illustrating some of the tests which have been made at the Watertown Arsenal laboratory.||

On Fig. 200 the heavy vertical lines represent the number of loads which were applied to a number of steel bars of .55 per cent carbon, and which

* Phil. Trans. Royal Society of London, A-Vol. 199, p. 265, 1902.

† Proceedings Inst. of Civil Engrs., Vol. 166, p. 78, 1906.

‡ Various Methods of Determining Dimensions. Dr. J. Weyrauch; translated by G. R. Bodmer. Proc. Inst. C. E., 1882–83, Vol. LXXI.

§ Résumé de la Société des Ingénieurs Civils, 1882.

|| Notes on the Endurance of Steels under Repeated Alternate Stress. Howard, Proceedings Am. Society for Testing Materials, 1907, Vol. VII.

caused rupture of the metal. Beginning with the highest fiber stress, 60,000 pounds per square inch, the progressive gain in endurance of the steel as the loads were successively reduced will be noted, as indicated by the lengths of the different lines. The lowest fiber stress experimented with did not end in

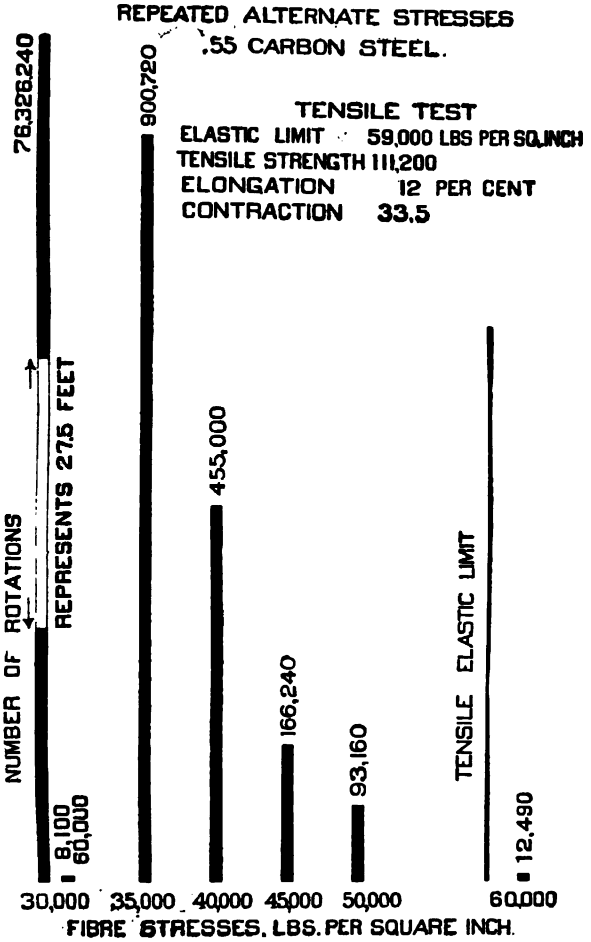


FIG. 200. — Behavior of 0.55 Carbon Steel under Repeated Alternate Stresses. (Am. Soc. for Testing Materials.—Howard.)

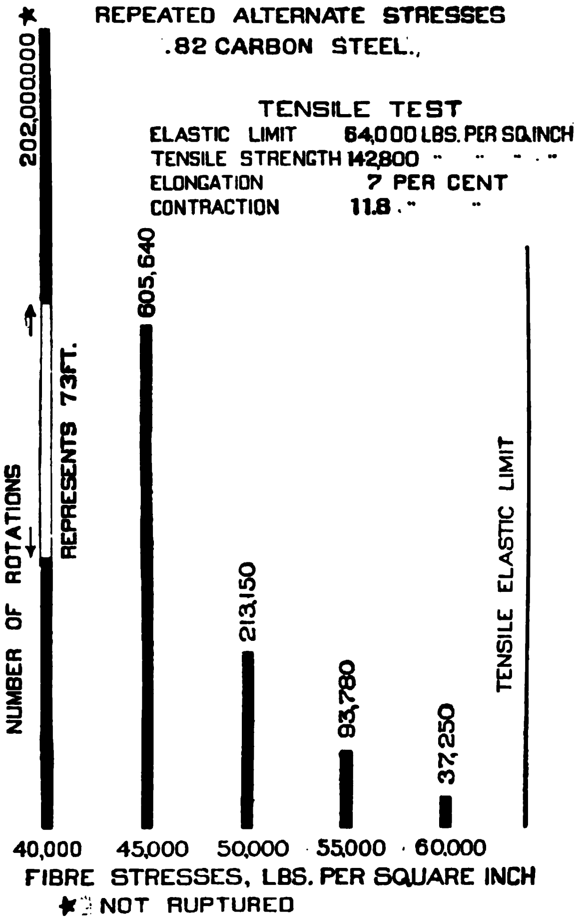


FIG. 201. — Behavior of 0.82 Carbon Steel under Repeated Alternate Stresses. (Am. Soc. for Testing Materials. — Howard.)

rupture of the shaft; after 76 million repetitions, in round numbers, under a load of 30,000 pounds per square inch, the fiber stress was increased to 60,000 pounds per square inch, which higher load caused rupture after about 8000 rotations. The enormous gain in endurance of the steel, under 30,000 pounds fiber stress, over its behavior with the higher loads, would be represented by a vertical line about 28 feet in height, according to the scale of this diagram. The results of the tensile tests of this grade of steel are entered on the diagram,

from which it may be seen that the several fiber stresses were, with one exception, below the tensile elastic limit of the metal.

On Fig. 201 similar lines represent the behavior of specimens containing .82 per cent carbon. The behavior of this grade resembles that of the previous diagram, and similar to other steels belonging to this series of experiments. The endurance under corresponding loads is seen to be greater than displayed on the preceding diagram. After making 202 million rotations the test of the shaft loaded with 40,000 pounds was temporarily discontinued, the steel being unruptured. A line drawn to scale to represent the endurance under this load would be about 73 feet in height.

On Fig. 202 appear curves representing the relative endurance of each of the six grades of steel used in this series of experiments. Their endurance under the higher fiber stresses only are shown, loads which caused comparatively early rupture of the steel in most of the tests.

It may be remarked that the fiber stresses experimented with were generally below the tensile elastic limits of the steels. The greater endurance of the steels of .73 and .82 per cent carbon in comparison with either the higher or the lower carbons is an interesting feature of the tests.

Elastic properties only are displayed by steels, prior to rupture when rupture is caused by a large number of alternate stresses of tension and compression; no appreciable display of ductility, as shown by elongation and contraction of area, need precede rupture, in any grade of steel, following the application of stresses of this kind. If the fiber stresses somewhat exceed the tensile elastic limit, a limited display of elongation, other than elastic, may occur, but rupture caused by loads which are in the vicinity of or below the tensile elastic limit is not attended with an appreciable display of ductility.

While tests by repeated alternate stresses are characterized by the absence of ductility, as witnessed in tests by tension, there may be elastic movements of the metal aggregating considerable distances. The aggregate extension of the most strained fiber of the .82 per cent carbon steel which has successfully endured 202 million repetitions amounts to nearly 5 miles per linear inch of specimen, a distance quite incomparable to the permanent extension of the metal in the tensile test.

* Little attention seems to have been given to the possibility of finding a relation connecting the stress used in endurance tests with the number of repetitions required for rupture. Spangenberg, Reynolds, and Smith, and

* The Exponential Law of Endurance Tests, O. H. Basquin, Proceedings of the American Society for Testing Materials, 1910, Vol. X, p. 625.

Stanton and Bairstow, have shown stress-repetition curves drawn to ordinary Cartesian coördinates.

Logarithmic coördinates present a distinct advantage in the study of simple exponential curves, because these curves become straight lines for these

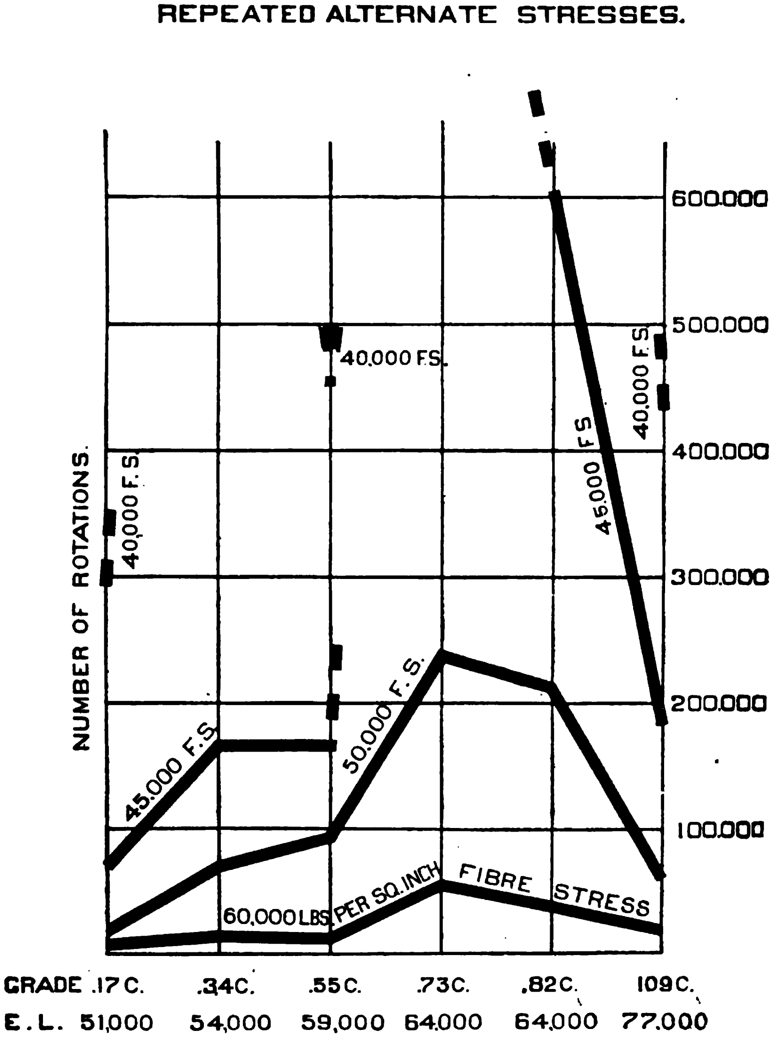


FIG. 202. — Comparison of the Behavior of Different Grades of Steel under Repeated Alternate Stresses (Am. Soc. for Testing Materials. — Howard.)

coördinates and their equations may be written at once. Fig. 203 shows stress-repetition curves for nineteen sets of endurance tests, made by five different observers. The names of the experimenters, the kind of test, and the material are given in Table LXX.

TABLE LXX.—EXPERIMENTS ON REPEATED STRESS

(Basquin)

Curve Letter.	Experimenter.	Kind of Test.	Material.	Coefficient (Thousands) C.	Exponent n.
A	Wöhler..........	*a*	Wrought-iron axles, Phoenix Co....	217	−0.12
B	"	*b*	Wrought-iron axles, Phoenix Co....	109	−0.10
*C**	"	*b*	Cast steel, Borsig..................	103	−0.09
*D**	"	*b*	Cast steel, Borsig..................	94	−0.11
E	"	*b*	Homogeneous iron, P. C. & Co.....	130	−0.12
F	"	*b*	Bar copper, Heckmann............	36	−0.08
G	"	*b*	Cast iron, locomotive cylinder.....	29	−0.09
H	"	*a*	Krupp's spring steel, hardened.....	1000	−0.20
J	"	*a*	Krupp's spring steel, unhardened...	920	−0.21
K†	"	*c*	Krupp's axle steel................	320	−0.15
L†	"	*c*	Krupp's axle steel................	310	−0.18
M	"	*b*	Krupp's axle steel................	90	−0.07
N	"	*b*	Cast steel, Vickers & Sons.........	97	−0.08
O	Benjamin Baker.....	*d*	Bars from Forth Bridge...........	115	−0.10
P	" "	*b*	Hard steel........................	250	−0.15
Q‡	Reynolds & Smith ..	*e*	Annealed cast steel...............	102	−0.13
R‡	" " ..	*e*	Annealed mild steel...............	66	−0.11
S§	F. Rogers..........	*b*	Unannealed steel..................	110	−0.08
T	Föppl..............	*b*	Steel A, grooved..................	150	−0.15
U	"	*b*	Steel B, grooved..................	135	−0.14

* *C* has round shoulders near grip; *D* has square shoulders.

† *K* has round shoulders near grip; *L* has square shoulders.

‡ Ordinates are "Half Range of Stress," instead of maximum stress.

§ Carbon, 0.32 per cent; yield point, 39,000 pounds per square inch. Most points show the mean of more than one test.

Kinds of Tests:

(a) Bending in one direction only (+ and 0).
(b) Rotating under bending load (+ and −).
(c) Tension only (+ and 0).
(d) Bending back and forth (+ and −).
(e) Tension and smaller compression (+ and −).

The curve *A* is represented by the equation

$$S = 217{,}000\ R^{-0.12},$$

which has the form

$$S = CR^n,$$

in which S is the maximum stress used in each test and R is the number of repetitions of this stress required for rupture. The coefficient, 217,000, was found by extending the line A to the left until it intersected the vertical line $R = 1$ (i.e., 10°), and the stress at this intersection was read off the logarithmic scale as 217,000 pounds per square inch. The coefficient is the stress given by the curve for a single repetition. All the coefficients given in Table LXX in the column marked C were found in the same way. The value of the exponent, −0.12, was found by measuring the angle (130°) which this line makes with the horizontal axis and then taking one-tenth of its natural tangent. The factor "one-tenth" comes in because, in Fig. 203, the scale used along the vertical axis

in plotting the stresses is ten times the scale used along the horizontal axis in plotting the repetitions. In the same way the exponent for each curve of Fig. 203 has been found and is listed in the table under the column marked n.

In looking over the curves, Fig. 203, it is evident that in many cases the straight line represents the results of endurance tests very accurately throughout a considerable range of stress. One is also impressed with the approximate

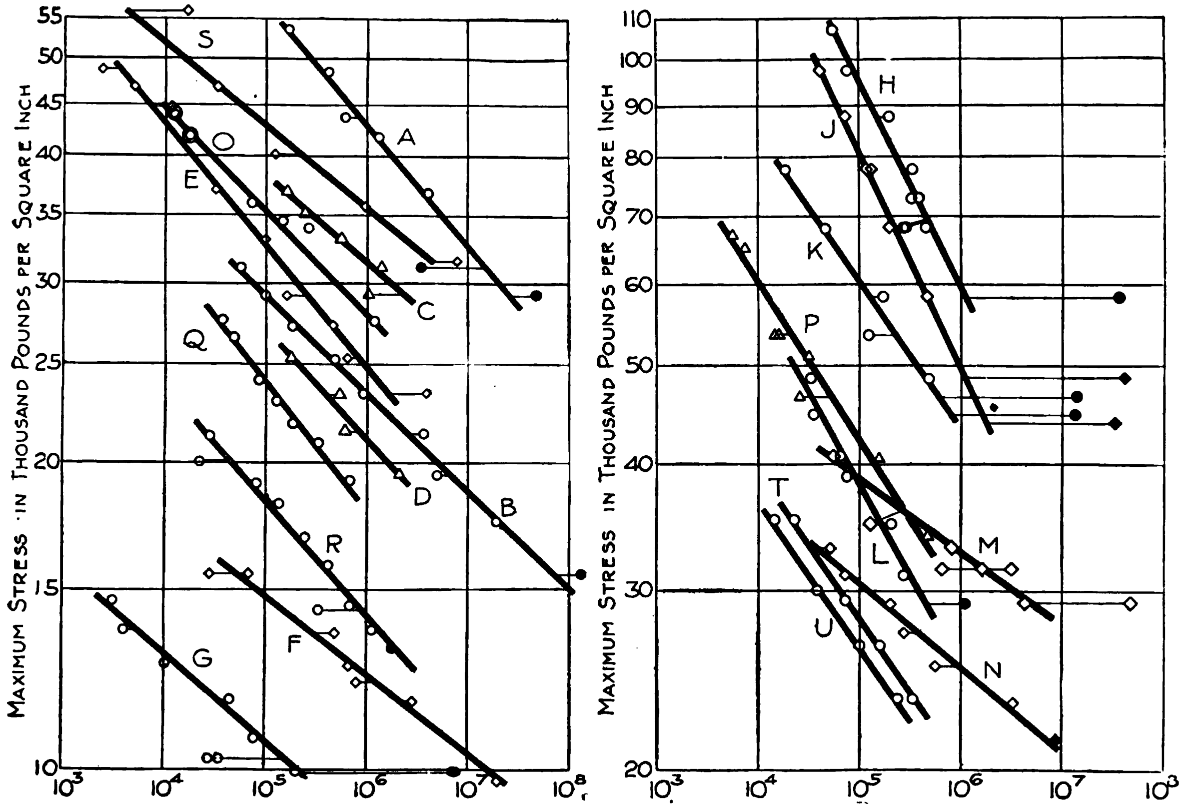


FIG. 203. — Number of Repetitions before Rupture in Endurance Tests of Metals. (Am. Soc. for Testing Materials. — Basquin.)

parallelism of many of these lines. Curves B, C, D, E, F, G, M, N, and S represent tests made in much the same way, — by rotating a specimen under bending load. The curve for hard steel, tested by Baker * in much the same way, has a steeper slope; the same is also true of the grooved specimens tested by Föppl.† Curves H, J, K, and L are approximately parallel and represent tests in one direction only; i.e., the stresses are not reversed. They have about

* Some notes on the Working Stress on Iron and Steel, Trans. Am. Soc. of Mech. Engrs., 1887, Vol. VIII, p. 157.

† Mitteilungen aus dem Mech. Engrs., Vol. 130, 1909.

double the slope of the other curves mentioned. Why curve A, on wrought iron, does not fall into this class is not clear.

* Small changes in temperature occur when a bar of metal is stressed within the elastic limit, it becoming cooler under tension and warmer under compression. The measurements of these changes made by Turner, in 1902, have shown that these changes in temperatures continue at a uniform rate up to about three-fifths of the elastic limit, and that then a marked change occurs, the bar under tension then beginning to grow warmer, while the temperature of the bar under compression increases at a more rapid rate.

It thus appears for stresses higher than above three-fifths of the elastic limit, at least, energy is converted into heat under repeated applications; probably this occurs also at lower stresses when repeated stresses range from tension into compression in a bar, or when a beam is subjected to alternating flexure.

In the case of the rail the bending stress alternates about in the proportion of 4 to 1, and it is very probable that by taking a unit stress less than half the elastic limit, we may safely ignore the effect of fatigue on the metal of the rail produced by this stress. The disturbed metal at the running surface of the head which is frequently conspicuous in old rails is evidence of the elastic limit of the metal being exceeded rather than the effect of repeated stress below this limit. Generally speaking the effect of repeated stress is not to produce distortion of the metal, and prior to rupture elastic properties only are displayed.

26. Effect of Low Temperatures on the Strength of the Rail

Very complete investigations were made to determine the effect of changes of temperature in modifying the physical properties of iron and steel by Styffe and Sandberg.† The conclusion of Styffe is that the strength of iron and steel is not diminished by cold. Arguing from these experiments, investigators have assumed that the cause of the frequent breakage of rails in cold weather, and of articles made of iron and steel, is unequal expansion and contraction and the rigidity of supports, where, as in the case with rails, frost may very greatly affect them.

‡ Sandberg, while admitting the care and the accuracy which distinguished this extensive series of experiments, still doubted whether the reasons just

* Mechanics of Materials, Merriman, p. 354, New York, 1905; and Trans. Am. Soc. of Civil Engrs., Vol. XXVIII, 1902, p. 27, Thermo Electric Measurements of Stress, Turner.

† The Elasticity, Extensibility, and Tensile Strength of Iron and Steel, by Knut Styffe, translated from the Swedish, with an original appendix by Christer P. Sandberg; with a preface by John Percy, M.D., F.R.S., London, 1869. (Sandberg's investigations appear in the appendix.)

‡ Iron and Steel; Materials of Engineering, Thurston, 1909 p. 556.

given were the sole reasons why metals should more readily break in cold than in hot weather, and, having obtained the consent of the State Railway Administration, he conducted a series of experiments in the summer and winter of 1867, at Stockholm, to determine whether, with equal rigidity of supports, iron rails would yield with equal readiness to blows at the two extremes of temperature.

The rails experimented upon were each cut in halves, and one piece was tested in cold and the other in warm weather, at temperatures of 10 degrees and 84 degrees Fahr. respectively. The supports at the end of the rails were granite blocks placed four feet apart, and resting on the smoothly leveled surface of the granite rock. They were broken by a heavy drop weighing 9 cwt.

Sandberg's conclusions from twenty experiments are thus given:

"(1) That for such iron as is usually employed for rails in the three principal rail-making countries (Wales, France, and Belgium), the breaking strain, as tested by sudden blows or shocks, is considerably influenced by cold, such iron exhibiting at 10 degrees Fahr. only from one-third to one-fourth of the strength which it possesses at 84 degrees Fahr.

"(2) That the ductility and flexibility of such iron is also much affected by cold; rails broken at 10 degrees Fahr. showing, on an average, a permanent deflection of less than one inch, whilst the other halves of the same rails, broken at 84 degrees Fahr., showed a set of more than 4 inches before fracture.

"(3) That at summer heat the strength of Aberdare rails was 20 per cent greater than that of the Creusôt rails, but that in winter the latter were 20 per cent stronger than the former."

Sandberg suggests that this considerable lack of toughness at low temperatures may be due to the "cold-shortness" produced by the presence of phosphorus.

Jouraffsky, of St. Petersburg, has reported* the results of tests of rails made for the Russian government, which supplement the preceding in a very valuable manner. It was found that by placing pieces of rail from 6 feet to 8 feet long in a mixture of ice and salt, the temperature of the rail could be lowered in a very short space of time, during warm weather, 36 degrees Fahr. below freezing point.

A special commission, Messrs. Erakoff, Beck, Guerhard, Nicolia, and Feodossieff, was appointed to carry out a series of tests on this plan. Pieces of rail 6 feet long were taken in pairs, one of which was tested at the natural temperature, the others being placed in a box filled with a mixture of

* Communicated to the London Meeting of the Iron and Steel Institute, 1879.

two parts of broken ice and one part of salt, and, after being cooled to a temperature of from +3 degrees to −6 degrees Fahr., which occurred in half an hour, they were all submitted to the same tests. Altogether, 86 samples were tested, and these were, for the sake of comparison, divided into two groups, viz.: (1) Rails which broke under the test; and (2) rails which stood the test.

The results indicated that the brittleness of the steel increases very much at low temperature if it contains more than a moderate amount of phosphorus, silicon, and carbon. The total of the three elements in the rails which broke under the test averages 0.54 per cent, and in those which stood the same test 0.41 per cent, the first average (0.54 per cent) varying from 0.44 to 0.67 per cent, and the second average (0.41 per cent) varying from 0.37 to 0.55 per cent.

The tests on steel at different temperatures made at the Watertown Arsenal in 1888,* showed within the range of 0.37 to 0.71 per cent carbon a slight increase in the elastic limit and tensile strength at 0 degrees Fahr. above that at summer heat, accompanied by very little change in the elongation or contraction of area.

Dr. P. H. Dudley recommends the use of basic open-hearth rails of 0.62 to 0.75 carbon with phosphorus under 0.04 to insure a more uniform range of toughness and ductility of metal where exposed to low temperatures than has been obtained in plain Bessemer with 0.50 carbon and 0.10 phosphorus.

Tests of Bessemer heats were made in which one-tenth of one per cent of metallic titanium was added to the steel and the carbon increased from 0.50 to a range of 0.60 or 0.70, the metal having higher physical properties and toughness at the same time. The manganese and silicon are lowered slightly to prevent shrinkage cavities in the ingots.

Tests were made under the drop comparing the ordinary Bessemer rails and this grade of steel cooled to zero temperatures, and some specimens were also cooled to 22 degrees Fahr. below zero. The tests of the Bessemer steel with the one-tenth of one per cent of metallic titanium withstood a drop of 2000 pounds, falling sixteen feet without breaking, while the plain Bessemer would fail at the low temperatures at about one-half that height.

Dr. Dudley † considers that basic open-hearth rails (C = 0.68; Mn = 0.86; Si = 0.10; P = 0.012) which show ductility ranging from 15 to 20 per cent under the drop test are proper for use under high-speed trains where the temperature in winter falls to 20 degrees Fahr. below zero.

* Tests of Metals, 1888, House Doc. No. 45, 50th Congress, 2nd Sess., p. 505.

† Dudley on Ductility Tests on Rails. Proceedings American Society for Testing Materials, Vol. X, 1910, p. 229.

The question of obtaining a proper amount of ductility in rails, used in cold climates, is a very important one. The experience of the railroads in the Northern and Western States, during the very cold weather of the winter of 1911–1912, was more severe than ever before reported. The effects were so great that rails which had heretofore been quite free from breakages were broken in considerable quantities by the wheels of the passing trains. The record of rails of large ductility or tenacity and toughness, on the other hand, showed a much greater freedom from breakages.

With the recently adopted standard drop-testing machine (see Article 27) the ductility of the rail can be measured with much more accuracy than was possible in the machines which preceded it. With the older machines the rebound of a 2,000-pound hammer was as large as 12 to 14 inches, while in the present machine it is confined to 3 or 4 inches.

The maximum elongation per inch can be obtained by stamping the base, head, or edge of the base of the butt, as the case may be, before testing with a spacing bar of six inches, directly under the point of impact for either a single blow or for two or more required to exhaust the ductility of the metal. These six inches include about two-thirds of the metal affected by the impact.

The elongation in the base of a 6-inch, 100-pound rail, with a moment of inertia of 48.5, under a single blow for an 18-foot fall in the present drop-testing machine, will be from 6 to 7 per cent for a steel of 0.50 carbon, 0.10 phosphorus, and 1.00 manganese. The elongation of the metal under the drop-testing machine compares favorably with that obtained by static loads in the tension machine. The tendency is an increase of possibly one or more per cent, owing to the fact that the base of the rail in stretching does not neck as in the case of a tensile specimen.

To raise the mean ductility, it has been found necessary to reduce the average percentage of carbon in heavy sections to 0.50, when the phosphorus content is 0.10, for rails which are to be used where the temperatures fall below zero. The Bessemer rails, owing to the greater content of phosphorus, oxides, and nitrogen, show a greater tendency to irregular low ranges of ductility than the basic open-hearth rails. The use of ferro-titanium in Bessemer steel, to take up a large percentage of the oxides and also a part of the nitrogen, makes it possible to increase the carbon content without any sacrifice to the ductility.*

Probably some of the failures of rails in cold weather can be attributed to the effect, already noted in article 24, of the contraction of the metal, which may set

* The subject of ductility in rail steel has been reported upon very fully by Dr. P. H. Dudley in papers presented to the American Society for Testing Materials, see Proceedings, Vol. X, 1910, pp. 223–232, and Vol. XI, 1911, pp. 454–461.

up tensile stresses of some magnitude in the rails before the ends render in the splice bars.

The effect of frost, in heaving the track where the ballast or subgrade contains much moisture, is to cause an irregular surface and, on account of some of the ties rising or "heaving" above the others, often produces larger bending moments in the rail than would be expected if the ties were free to adjust themselves to the elastic curve of the rail. In the case of well-drained track, on stone ballast, where heaving is absent, smaller bending moments will be found in the frozen track than when in its natural condition.

27. Physical Tests of the Strength of the Rail

The impact hammer or drop test, introduced by Sandberg and Styffe, in 1868, is most generally used in this country in testing the strength of the rail.

From the very prominent place given drop tests in rail specifications,* it might be seen that the behavior of the rail under the drop test is generally regarded as valuable information as to its character. As a matter of fact, however, engineers differ widely as to the advisability of accepting this test as an index to the reliability of the rail, on account of the great variation in the results obtained. The test shows, it is true, whether the piece being tested is brittle or not, and by observation of the permanent set, whether the steel

Note. For an account of the state of knowledge relating to impact tests and for a bibliography of literature, reference is made to the following:

American Section, International Association for Testing Materials: Bulletin No. 5, October, 1899. Report of Committee on Present State of Knowledge Concerning Impact Tests. W. K. Hatt and Edgar Marburg.

Bibliography on Impact Tests and Impact Testing Machines. Proceedings American Society for Testing Materials, Volume II, page 283. W. K. Hatt and Edgar Marburg.

The Resistance of Metals under Impact. Mansfield Merriman. Proceedings American Association for the Advancement of Science, Volume 43, 1894.

Theory of Impact and its Application to Testing Materials. H. D. Tiemann. Journal of the Franklin Institute, October and November, 1909.

International Association for Testing Materials, Vth Congress, Copenhagen, 1909. Impact tests papers, III_1, III_2, III_3, III_4, III_5, III_6, III_7, III_8.

Elongation and Ductility Tests of Rail Sections under the Manufacturers' Standard Drop-Testing Machine. P. H. Dudley, Proceedings American Society for Testing Materials, Vol. X (1910), p. 223.

The Same. Iron Trade Review, Vol. 47, p. 410.

Nouvelle Methode d'essai des Rails, Ch. Frémont Génie Civil, Vol. 59 (1911), p. 7, 26, 48, 72.

The same. Railway Age Gazette, Vol. 51, p. 1176.

New Types of Impact Testing Machines for Determining Fragility of Metals. T. Y. Olsen. Proceedings American Society for Testing Materials, Vol. XI (1911), p. 815.

* Some Results Showing the Behavior of Rails under the Drop Test, and Proposed New Form of Standard Drop Testing-Machine. S. S. Martin. Proceedings Am. Soc. for Test. Materials, 1908, Vol. VIII.

is soft or hard. Recent work in Germany and France points to the conclusion that some form of impact test is found necessary to detect faults of structure that are not evidenced by the static test.

Average specifications, which a majority of the railroads have in recent years used as a standard, contain the following clause as to drop test:

One test shall be made on a piece of rail, not less than 4 feet, nor more than 6 feet, selected from each blow of steel. The test piece shall be taken from the top of the ingot. The rails shall be placed head upwards on the supports, and the various sections shall be subjected to the following impact tests under free falling weight:

70 to 79 pound rail,	18-foot drop.
80 to 89 pound rail,	20-foot drop.
90 to 100 pound rail,	22-foot drop.

If any rail breaks, when subjected to the drop test, two additional tests may be made of other rails from the same blow of steel, also taken from the top of the ingot, and if either of these latter rails fail, all the rails of that blow which they represent will be rejected; but if both these additional test pieces meet the requirements, all the rails of the blow which they represent will be accepted.

The drop-testing machine shall have a tup of 2000 pounds weight, the striking face of which shall have a radius of not more than 5 inches, and the test rail shall be placed head upward on solid supports 3 feet apart. The anvil block shall weigh at least 20,000 pounds, and the supports shall be part of or firmly secured to the anvil. The report of the drop test shall state the atmospheric temperature at the time the test was made.

These specifications, while used by the railroads, had to be modified according to the character of the drop-testing machines at the different mills. Thus, we find machines answering closely the following descriptions:

1. A drop-test machine consisting of some concrete and loose stone, supporting a number of 12 by 12 inch oak ties, 12 feet long, on which is placed an oak block 18 inches by 18 inches by 11 feet. On the oak block are two steel plates 1 by 18 inches by 7 feet, which become the bearings for the rail supports. These supports weigh 1300 pounds.
2. A drop-test machine consisting of a wooden foundation 4 feet deep and 10 by 10 feet, on which were placed two blooms, probably 8 by 10 inches by 10 feet. On the blooms are placed the rail supports.
3. A drop-test machine consisting of a concrete or stone foundation, on which rests a 20,000-pound anvil, to which the rail supports are securely fastened.

Up to within the last few years no rail mill has been equipped with a drop-testing machine for rails that was built on thoroughly scientific principles, owing to the lack of proper foundations or proper anvil, as well as many other essential details. Further, no two rail mills had machines built on even comparatively the same lines. Consequently, any exact determination of the loss of energy of the falling weight which is dissipated by the machine would have had no general application, and the results obtained from testing rails in the drop-testing machines of any two mills were not comparable.

The Manufacturers' Committee, recognizing these defects, prepared specifications and plans of a proposed standard drop-testing machine that will give satisfactory and comparable results, and the Rail Committee of the American Railway Engineering Association has, with certain small modifications and additions, approved these plans and specifications.

Specifications for Drop-Testing Machine

(See Fig. 204.)

1. The machine shall be arranged to allow a 2000-pound tup to fall freely at least 25 feet on the center of a rail resting on supports that can be adjusted to spans varying from 3 feet to 4 feet 6 inches.

2. The anvil shall be a solid casting, weighing, with the attachments that move with it, 20,000 pounds. It shall be free to move vertically independently of the lead columns and shall be supported on 20 springs known as the standard "C" spring, without center coil, as employed by the Master Car Builders' Association (their figure 5614). This spring has a free length of $8\frac{1}{4}$ inches, an outside diameter of $5\frac{7}{16}$ inches, and is made from a bar having a diameter of $1\frac{3}{16}$ inches. These springs are to be arranged in groups of five at each corner of the anvil and are to be held in place by hubs raised on the top of the base plate and by circular pockets on the under side of the anvil. Anvil to be guided in its vertical movement by removable finished wearing strips, these strips to be suitably attached to the finished edges of the column base.

3. The base plate shall be of cast iron or cast steel, 8 inches thick in the area covered by the anvil. It shall be firmly secured to the substructure by four bolts 2 inches in diameter.

4. The substructure shall consist of a timber grillage resting on a masonry foundation. The grillage shall project 9 inches beyond the ends of the base plate, and clear the columns at the side. It shall consist of one course of 12 inches by 12 inches sound oak or southern yellow pine, preferably creosoted, laid close and well bolted together. The masonry, preferably concrete, shall not be less than 5 feet deep below the grillage and be suitably supported on the subsoil.

5. The pedestals for supporting the test rail shall be substantial castings, and the surface of the anvil between these pedestals shall be formed to receive a wooden block to absorb shock under broken pieces. The rail supports shall be removable pieces of steel securely held in the pedestals having an upper cylindrical bearing surface with a radius of 5 inches. The pedestals shall be adjustable to spans, varying from 3 feet minimum to 4 feet 6 inches maximum between centers. They shall be securely held together and so fixed to the anvil as to insure that the center of span shall always coincide with the center between leads.

6. The leads shall be firmly connected to the base plate and well braced. They shall be long enough to provide the prescribed free fall of the tup. They shall be provided with a convenient ladder and a plainly marked gauge, divided into one-foot intervals. The zero of this gauge shall be $5\frac{1}{4}$ inches above the top of the rail support, and the specified height of drop shall be measured from this zero, irrespective of the height of the rail being tested. One of the guides shall have a removable section, 6 feet long at the bottom, so that the tup or tripping block can be readily removed.

7. The tup shall weigh, with the accessories that drop with it, 2000 pounds. The striking die shall be steel having a cylindrical striking face with radius of 5 inches and a length of 12 inches. The guide grooves shall have finished surfaces. The tripping head shall allow a grip of the tongs that will release at the exact height for which the tripping device is set and that will be safe from accidental release while the test piece is being shifted.

8. The tongs and tripping device shall be arranged to release the tup automatically only; no manual releasing will be allowed. The tripping device shall be easily adjustable at one-foot intervals.

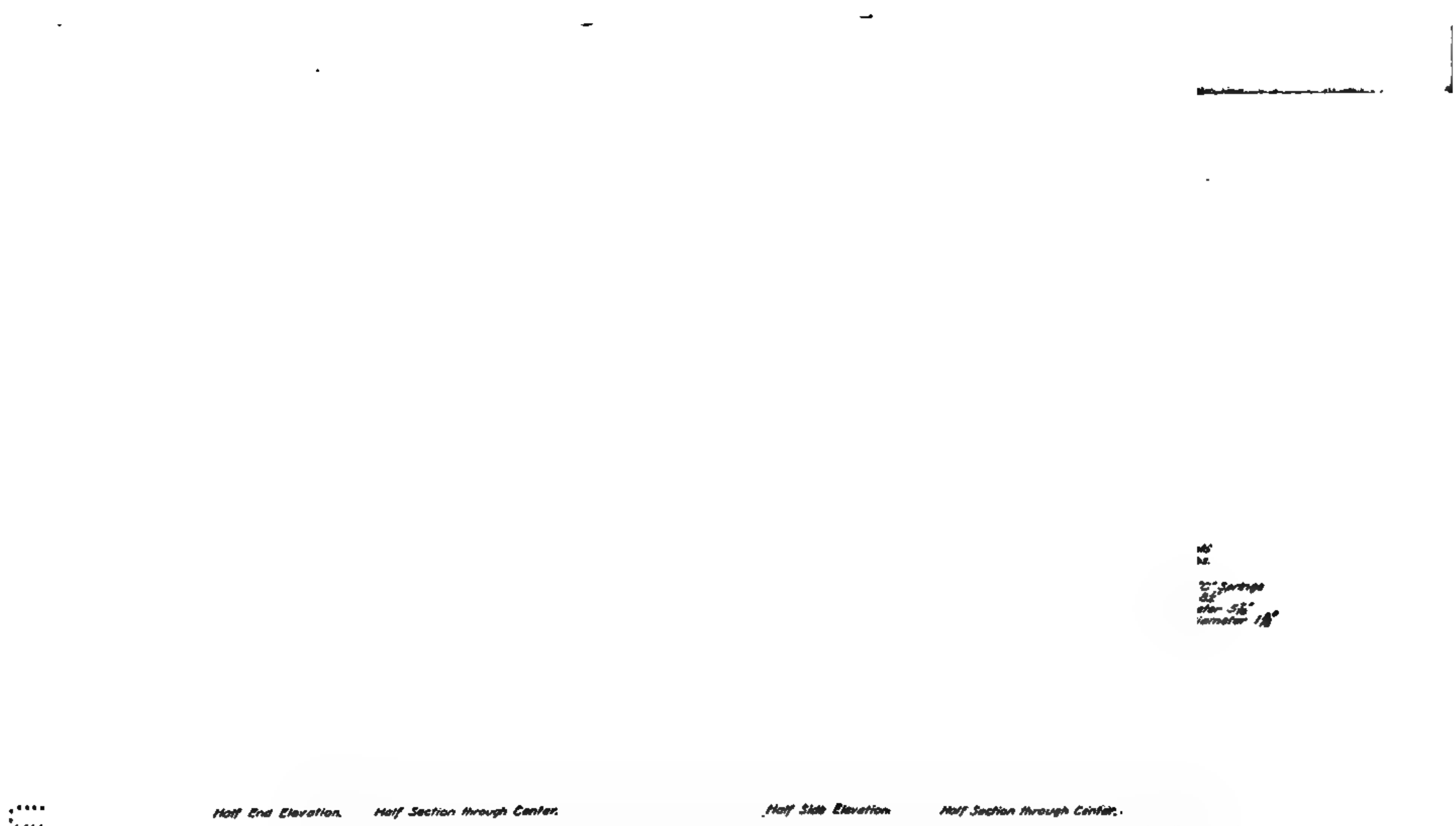


FIG. 204.—Standard Drop Testing Machine, as adopted by Committee of Rail Manufacturers of the United States, April 8, 1908. Recommended by Committee on Rail of the American Railway Engineering Association at Meeting of June 26, 1908. Adopted by the Association, Vol. 10, Pt. 1, 1909, pp. 369–373, 375, 395, 396; Vol. 11, Pt. 1, 1910, pp. 240, 252, 562.

Sellew. "Steel Rails."

A diagram showing graphically the relation between results of tests as between the old and new methods, furnished by Mr. Thomas H. Johnson, is given in Fig. 205.

These tests were made on rails of the same grade of steel, viz., carbon, about .50, and manganese, .90 to 1.00. All of the tests were made with a

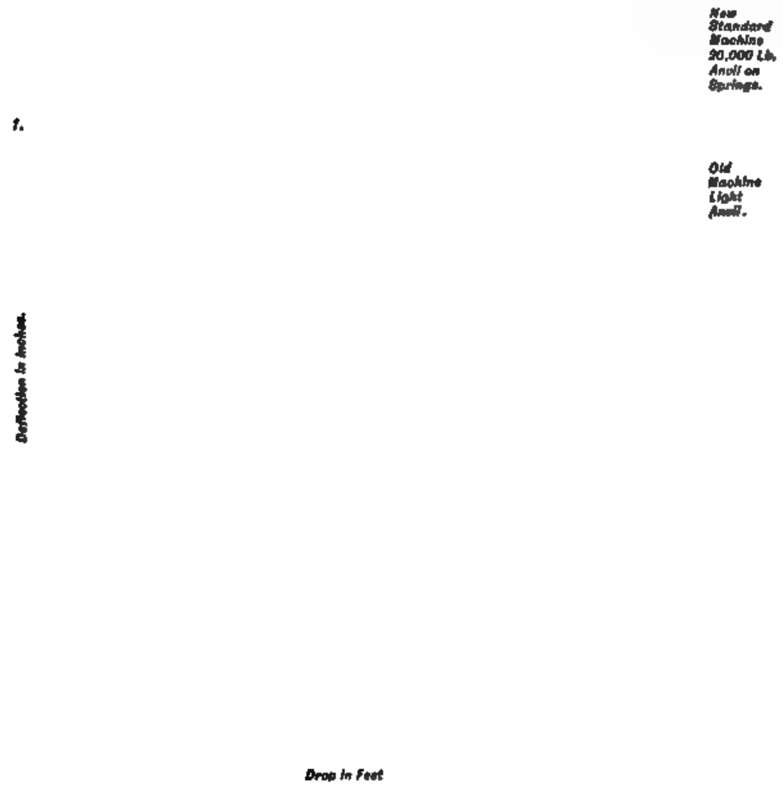


FIG. 205. — Diagram of Tests with Drop-Testing Machines of Old and New Design. (Johnson.)

2000-pound tup, with a radius of striking face 5 inches, and span between centers of supports 3 feet. Table LXXI gives the result of these tests.

Since 1908 a number of machines of this design have been installed at various mills with satisfactory results. The introduction of a standard drop-testing machine has been of such benefit to the manufacturers and consumers of this country that the International Association for Testing Materials has published a description and cuts of the American Standard drop-testing machine in French, German, and English.* The seventh London Resolution of the Council was as follows:

> "That a standard drop-testing machine for rails be adopted in each country, as has already been done in the United States, in order to make tests comparative."

* Proceedings, Vol. 11, No. 4, May 20, 1911, p. 237.

If we consider what occurs in dealing the blow on the rail with the falling weight, it will be seen that the work utilized by the rail in order to take a corresponding set is not the potential energy of the weight at the moment when the weight touches the bar. The energy of the falling weight serves to deform the rail, to compress the supports, the body of the drop weight, the anvil, and the ground upon which the anvil is placed.

TABLE LXXI.—TESTS ON NEW AND OLD DROP-TESTING MACHINE OF P. R.R. AND P. S. RAIL SECTIONS

(Am. Ry. Eng. Assn.)

Height of Drop.	New Standard Machine.				Old-Style Machine.			
	P. R.R. 85-Pound Set.	P. S. 85-Pound Set.	P. R.R. 100-Pound Set.	P. S. 100-Pound Set.	P. R.R. 85-Pound Set.	P. S. 85-Pound Set.	P. R.R. 100-Pound Set.	P. S. 100-Pound Set.
Feet.	Inches.	Inches.	Inches.	Inches.	Inches.	Inches.	Inches.	Inches.
.5	.02	.02	.02	.02	.0	.0	.0	.0
1	.08	.08	.08	.06	.031	.0	.031	.0
1.5	.16	.17	.14	.15	.093	.062	.062	.031
2	.25	.22	.19	.19	.125	.093	.125	.093
3	.38	.37	.28	.25	.250	.171	.218	.109
4	.49	.47	.40	.38	.343	.250	.281	.250
5	.60	.53	.50	.45	.406	.343	.375	.312
6	.76	.66	.64	.62	.513	.468	.437	.375
7	.88	.76	.74	.70	.700	.600	.650	.375
8	.99	.90	.86	.81	.800	.700	.700	.600
9	1.12	1.01	.98	.90	.900	.800	.750	.700
10	1.20	1.13	1.06	1.02	1.000	.850	.800	.800

Breuil* has shown that for the same amount of actual work the bending curve of the impact test is the same as the slow-bending test, and Hatt† has observed that there is little difference in the total elongation and unit rupture work whether the bar is ruptured in ten minutes or in from one to two one-hundredths of a second.‡

* Relation between the Effect of Stresses slowly applied and Stresses suddenly applied in the Case of Iron and Steel. P. Breuil. 1904.

† Tensile Impact Tests of Metals. Hatt. Proceedings Am. Soc. for Test. Materials, 1904, Vol. IV.

‡ As further evidence we may quote the following opinions (Report on Impact Tests of Metals. Official report by G. Charpy, Montluçon, International Association for Testing Materials, 5th Congress, Copenhagen, 1909. McGraw-Hill Book Company, New York):

Captain Duguet writes: "The effect (of the duration of the stress) is very marked, especially during the period of great deformations; that would in itself suffice to render any too detailed investigation of the phenomena illusory. But we must not exaggerate the importance of this point. The extreme deformations are, in the case of soft steel, submitted to bending, very sensibly the same, whether they be produced slowly by hydraulic pressure or by the impact of a tup."

In his treatise on material testing, Professor Martens points out that, according to the experiments of Kick, the velocity of fall has only an insignificant influence on the magnitude of the deformation in impact bending tests. As regards tensile strength tests, Professor Martens concludes: "From the impact tension tests so far conducted in the Charlottenburg Laboratory, I have acquired the conviction that the deformations are produced exactly as by slow tension.

Fig. 206 shows the amount of energy dissipated in 90-pound A. R. A. type "B" Bessemer rails when tested in the drop-testing machine.*

The weight of the tup was 2000 pounds and the distance between supports three feet in both the dynamic and static tests. The anvil in the drop test weighed 10 tons, spring supported. Calculating the work done on the rail in the static test from the load deflection diagram, and in the drop test from the height of drop and weight of tup, it would appear from the lower diagram of the figure that about two-thirds of the energy of the falling tup is utilized to deflect this rail.

The difficulty of comparing the values of the stresses in impact tests with those which occur in static tests (i.e., where the momentum of the load does not factor) lies in the difficulty of accurately determining the value of the force acting between the hammer and the specimen in the former. Comparisons of the total work required to rupture a specimen, or to produce a given deflection, are comparatively simple.

The manner in which impact stresses are related to so-called static stresses requires careful theoretical consideration before it can be clearly comprehended. The author is indebted to the work of Mr. H. D. Tiemann † for the following presentation of the subject.

The rail tested by impact is in reality in the nature of a cushion between the two impacting bodies, namely, the tup A and the anvil B, and the anvil B must be of such proportions that its relative velocity v_b to that of the common center of gravity of itself and the tup, V, may be disregarded, as otherwise a correction must necessarily be made, which not only complicates the subject, but on account of the nature of the foundation of the anvil is almost impossible to apply.

In tension tests by means of several blows, we find often that the elongation was greater than in the slow-tension tests."

M. Lebasteur (Annales des Ponts et Chaussées, 1890) had likewise arrived at the following conclusions:

"1. The elongations observed in the fracture of bars under high-drop impact tests are nearly identical with the elongations of similar bars under slow tension.

"2. The appearances of the broken sections are absolutely the same in the two cases.

"3. The total intensities of the blows necessary to break bars under high-drop impacts are proportional to the dynamic resistance to rupture (as determined from the area of the curve of slow tensile stress);" and further on M. Lebasteur added that "the dynamic resistance to rupture measures the strengths of metals equally well for dynamic as for static stresses."

* Report, M. H. Wickhorst to Rail Committee of Am. Ry. Eng. & M. of W. Assn., Proceedings, Vol. 12, Part 2, p. 389–394.

† The Theory of Impact and its Application to Testing Materials, Journal of the Franklin Institute, October and November, 1909.

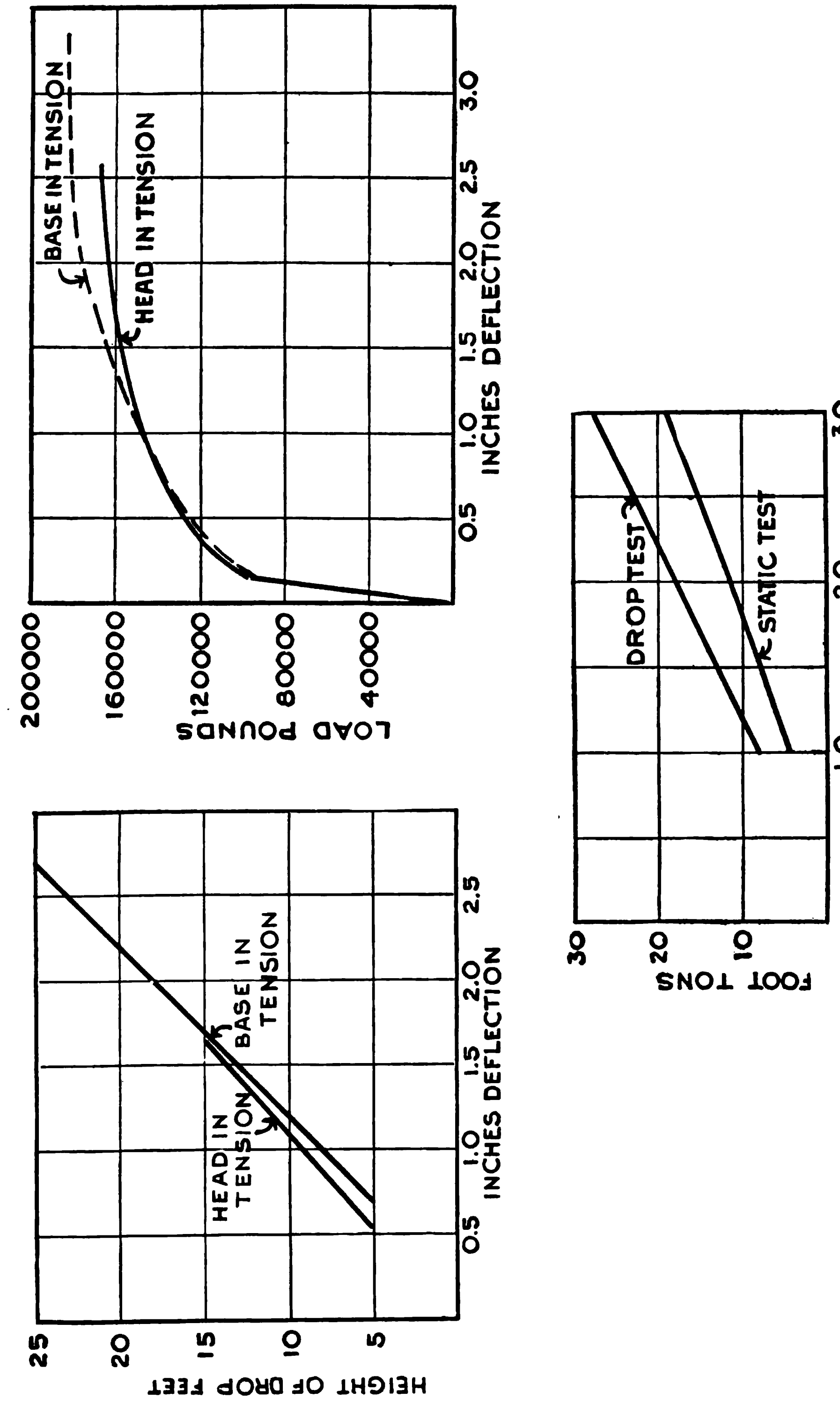


FIG. 206. — Relation of Work Done in Bending Rail in Drop and Static Tests. (Wickhorst.)

If we consider what occurs at impact, it is seen that at the beginning of contact a mutual repellant force F begins to come into play between A and B, which produces a change in the relative velocities $(v_a - V)$ and $(v_b - V)$, where

v_a = the velocity of A,
v_b = " " " B,
V = " " " the mutual center of gravity of A and B along a line joining their respective centers of gravity.

This force F, starting from 0 at first contact and increasing to a maximum when both relative velocities of A and B are brought to 0, then when rebound begins again decreasing until it becomes 0 at departure, is counterbalanced directly by the local compression of the material of both bodies at the point of contact.

This force is made up of two parts, one being the elastic resistance of the body to compression or deformation, f, and the other of the force necessary to produce the local acceleration of the particles compressed, f_1.

$$F = f + f_1.$$

At any instant F is exactly equal to the change in momentum produced by its action divided by the time required to produce this change:

$$F = \frac{m\,(v - v_1)}{t - t_1}.$$

Or more exactly,

$$F = \frac{mdv}{dt} = m\frac{d^2s}{dt^2} = ma,$$

where

m = mass,
s = space,
t = time,
v = velocity
a = acceleration.

Consequently, if the time-velocity curve can be determined, the force F can be calculated for any instant.

Let us examine first the relations between the various quantities of an impact test graphically, and then proceed to develop formulæ of the time-space curve and of the interrelations of the values.

Consider, first, a rail lying horizontally on the anvil B and supported freely at its ends, and let it be struck at the center by a falling tup A. For simplicity let us consider the rail as massless as well as weightless.

Take the velocities as relative to the anvil, as explained above, or assume the mass of the anvil so great that its motion may be taken as zero. Let the motion of the center of gravity of the tup A be plotted as in Fig. 207, with space as ordinates and time as abscissæ. If the tup start at some point J, and fall freely the distance H before striking the rail, the curve JB will be a parabola, or if its velocity be uniform its motion would give the straight line J_1B. Impact with the rail begins at B, and, assuming the rail as massless, the only resistance offered to the momentum of the tup will be the bending stress of the rail, which will be the force F. The motion curve then becomes

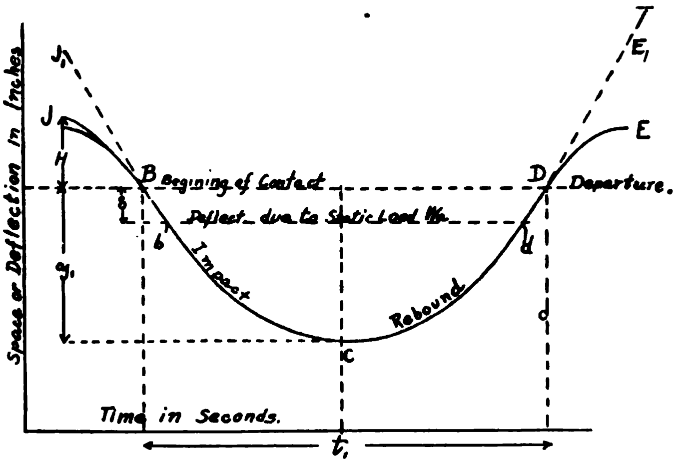


FIG. 207. — Time-deflection Curve, Massless Beam, within the Elastic Limit. (Journal of the Franklin Institute. — Tiemann.)

BC. The resisting force, starting with 0 at B, increases in proportion to the deflection of the rail until the maximum value is reached at C. (In this case, let the elastic limit of the rail be not exceeded.) It is this force F which overcomes the momentum of the tup A by producing a negative acceleration until the momentum is reduced to 0 at C. Rebound then begins. If the rail is perfectly elastic, the force F continuing to act will restore exactly the same amount of momentum to A, and in the same manner, but in the opposite direction that it had at the beginning of contact. The curve will be CD. At D departure takes place (the rail being considered as massless).

The total mutual repellent force F acting on the rail, between the tup A and the anvil B, is at any instant equal to

$$F = \frac{d^2S}{dt^2}A = \frac{dv}{dt}A,$$

where S is the space traversed by A and v is its velocity at the instant under

consideration. If S is in feet, t in seconds, and A = (weight in pounds ÷ acceleration of gravity in feet), then F is given in pounds, by the last formula.

If the force of gravity is to be considered, as well as the initial velocity of A at impact, then this formula should be written:

$$F - W_a = \frac{d^2S}{dt^2}A = \frac{dv}{dt}A,$$

where W_a is the weight in pounds of the tup A. This could be avoided by having the tup move horizontally instead of falling vertically.

Examining Fig. 207, it will be noted that the acceleration of the tup from J to B is equal to g and is produced by the uniform force W_a. From B to D it is produced by the force $W_a - F$ and becomes negative as soon as the value of F begins to exceed W_a. This is at the point of reverse curvature, since the acceleration

$$\frac{d^2s}{dt^2}$$

is zero, and evidently occurs at the point b or the deflection which would be produced by the static load W_a. In horizontal motion the change would occur at contact, B. It should be remembered that while W_a is a constant force, F is a variable, ranging from 0 at B, to a maximum at C, and again to 0 at D.

Whenever

$$\frac{d^2s}{dt^2}$$

becomes a maximum the force F becomes a maximum, and this evidently occurs at the sharpest part of the curve, which in this particular case is at C.

The value of F at any instant may, therefore, be determined from the curve

$$F = \frac{d^2s}{dt^2} \times A + W_a.$$

If the force F of the impulse becomes sufficient to cause complete failure of the specimen, the conditions are those shown in Fig. 208.

The first part of the curve JB is the same as before. The velocity or momentum of the tup is, in this case, not entirely overcome by the resistance F of the rail, so that at failure the tup retains a portion of its velocity as indicated by the tangent line DE_1. If the tup works vertically in free fall, instead of horizontally, then the curve DE is again a parabola of free fall. In this case the force F becomes a maximum at some point $\dot{C}$, when the curvature is sharpest, and must be determined from the curve by

$$\frac{d^2s}{dt^2},$$

since there is no means of calculating it mathematically.

The curve can be conveniently obtained by some mechanical device by means of which the falling tup makes a tracing on a uniformly revolving drum. When F is thus determined the maximum strength values may be calculated.

To supplement the information furnished by the drop test engineers are turning their attention to other means of testing the physical properties of the rail.

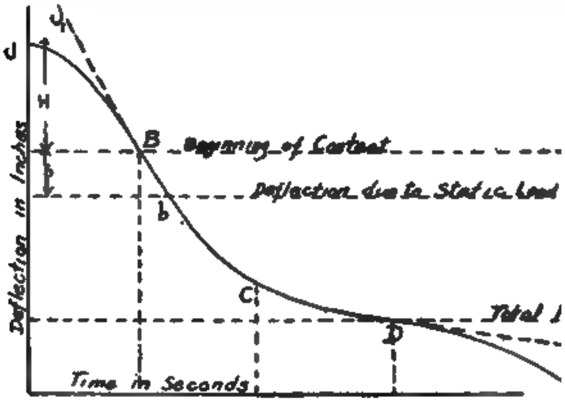


Fig. 208. — Time-deflection Curve, Beam Stressed be
Elastic Limit (Journal of the Franklin Institute. — Ti

* The Baltimore and Ohio Railroad Company, in connection with its investigations on rail, has been making use of the scleroscope (Fig. 209), an instrument for determining the degree of hardness of metals.

† The principle of the scleroscope (Greek *sclero* = hardness) consists of dropping a small plunger hammer from a fixed height onto the surface of the material whose hardness is to be measured. This hammer after striking, by no other force than its own weight, rebounds to variable heights, depending on the hardness or amount of resistance to penetration offered by the metal tested. The rebound of the hammer is used to measure the hardness of the metal, and the scale shown on the glass tube is simply for

Fig. 209.—Scleroscope. (Am. Ry. Eng. Assn.)

* General Information Concerning the Scleroscope and its Use on the Baltimore and Ohio Railroad. A. W. Thompson. Proceedings, Am. Ry. Eng & M. of W. Assn., 1910, Vol. 11, Part I.

† See also The Scleroscope, Albert F. Shore, p. 490, Proceedings American Society for Testing Materials, Vol. X, 1910.

comparative purposes and has no direct numerical value. This scale has 140 graduations, and a test of very hard steel has resulted in a rebound to the point marked 110, while soft brass results in a rebound to the point marked 12, and lead is about 2 per cent of hard steel.

Figs. 210, 211, and 212 present examples of tests. The numbers in these figures indicate the degrees of hardness.

Fig. 210 is an A. R. A. section of open-hearth rail, as rolled by the Bethlehem Steel Company, and is a new section which has not been in the track. It will be noted that the hardness on the top of the head of the rail is practically

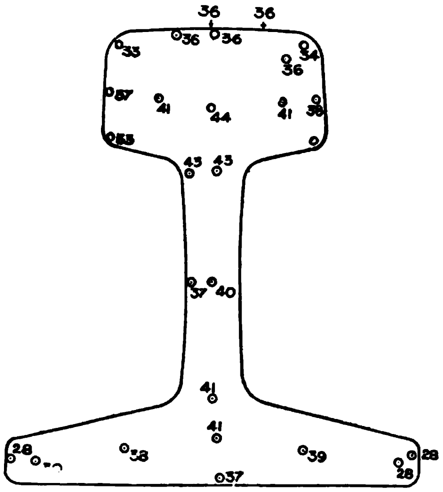


Fig. 210. — Scleroscope Tests on Open Hearth Rail (New.) (Am. Ry. Eng. Assn.)

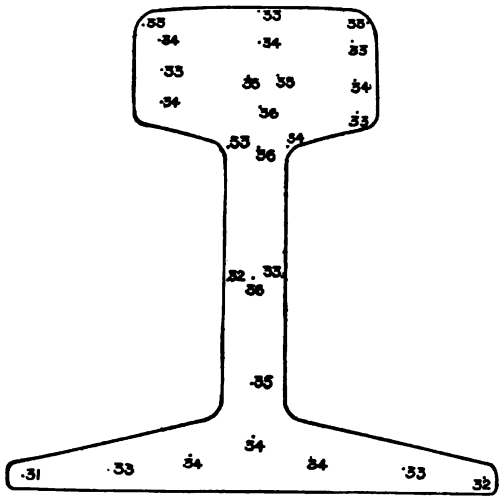


Fig. 211. — Scleroscope Tests on Bessemer Rail. (Am. Ry. Eng. Assn.)

the same as the steel in the section of the rail just below the surface. The center of the head appears to be the hardest, as well as a line through the center of the web and base. The upper corners of the head are comparatively soft, the ends of the base, however, being very much softer than any of the rest of the rail.

Fig. 211 is a section of a Bessemer rail rolled at Buffalo in 1908. It is a crop from the top end of a top rail. Although the specimen was from the top of the ingot, there is a difference of but three points in the readings throughout the head. The section, where polished and etched, showed rather dimly marked segregation. The head and base when planed into and etched showed some dark streaks in the head and light streaks and fissures in the base. The top of the head for $\frac{1}{8}$-inch depth was sound. The experimenter says: " The section as a whole is more uniform than is usually to be found in top, middle. or bottom rail of a Bessemer ' ingot.' "

Fig. 212 shows the comparative hardness on different lines on experimental titanium rails. This test indicates a skin of soft metal across the top of the head, but as soon as this is penetrated the hardness is reached, which compares favorably with any part of the whole section.

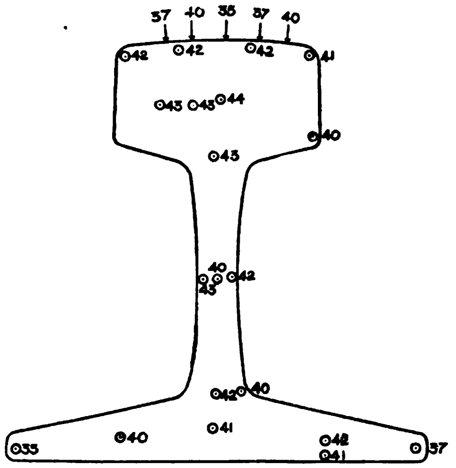


FIG. 212.—Scleroscope Tests on New Titanium Rail. · (Am. Ry. Eng. Assn.)

* Experiments were made at the laboratories of McGill University on the value of the indentation test for steel rails in regard to essential qualities desired in service. The study of this method of testing was suggested by tests made on a large number of rail sections by the Chief Engineer of the Canadian Pacific Railway, a spherical punch .75 inch in diameter being used, with a load of 100,000 pounds applied by an Emery testing machine for 10 seconds after commencing the load, and the indentation was measured by an instrument reading to $\frac{1}{1000}$ inch.

The tests, conducted by Mr. Dutcher, were on a set of bars of 2.5 by .75-inch section containing known percentages of carbon, which were verified by tests, and varied between .11 per cent and .96 per cent. The punches used (in addition to the foregoing) were a 60° cone, a 90° cone, and a paraboloid.

The term " hardness factor " applied to the results was obtained by dividing the projected area of the indentation on the surface of the specimen into the load applied. It was found that the yield point (as determined by tensile tests) varies directly as the hardness factor. The percentage elongation curve is also fairly straight between 200,000 pounds hardness factor (.10 per cent carbon steel) and 450,000 pounds hardness factor (about .70 per cent carbon steel); and the percentage of carbon varies directly with the hardness factor up to about .90 per cent.

† There have been several methods proposed to test the hardness of the metal by ball-pressure tests. In the Brinell test ‡ a hard ball of steel is forced

* Transactions of the Canadian Society of Civil Engineers, Dutcher, Vol. XXI, pp. 47–88.

† Hardness Tests. Official report by Dr. techn. P. Ludwik, of Vienna. International Association for Testing Materials, 5th Congress, Copenhagen, 1909. McGraw-Hill Book Company, New York, also various technical papers on Hardness Tests. Proceedings, American Society for Testing Materials, Vol. XI, 1911, pp. 707–743.

‡ Compare P. Ludwik, "Über Härtebestimmung mittelst der Brinnellschen Kugeldruckprobe und verwandter Eindruckverfahren," "Zeitschrift des österr. Ingenieur und Architekten-Vereines," 1907, Nr. 11 und 12 (Nr. 12, p. 205, extensive literature references).

by quiet pressure into the material to be examined; the diameter of the spherical impression is determined, as a rule, with the aid of a special microscope, and the area of the cavity is calculated. The quotient of pressure (in kilograms) by the area (in millimeters ^{2}) is Brinell's hardness number H.

The cone-pressure test marks a transition from the ball-pressure methods to scratch methods. It is the outcome of efforts to simplify the Brinell test, with the further object of making the hardness number independent of the load and of the dimensions of the impression.

In the Amsler-Laffon instrument (Fig. 213) a cylindrical steel center punch, plane above, ground to a right-angled cone below, is vertically mounted in a casing of bronze, in which it is free to turn; it is balanced by a lateral spring. The displacement of the cone (with regard to the casing) is transferred to a pointer by an elastic threaded bushing and a toothed wheel; the pointer allows of easily reading depths up to 5 millimeters within .01 millimeter. The pointer is accurately adjusted by turning it with the aid of the milled edge of the bushing, in case the top of the specimen should not be perfectly plane. The cone can easily be exchanged and be reground. The whole instrument weighs .7 kilogram ($1\frac{1}{2}$ pounds), and its height, from the upper pressure plate to the surface of the specimen, is about 10 centimeters (4 inches).

FIG. 213. — Amsler-Laffon Instrument for Measuring Hardness.

The question, whether the hardness numbers of a material, obtained by these methods, admit of any general conclusions respecting the strength of the material, and in particular the yield point and the tensile strength, is of high practical interest.

A direct constant relation between yield point and tensile strength on the one side, and hardness on the other, can not exist, since that relation would, among other factors, depend upon the shape of the impression and of the stress-strain diagram.

This admission does not, however, at all exclude the possibility of deducing from the hardness number, with the aid of a coefficient which will only hold

good between certain known limits, the yield point and the tensile strength with an approximation which will frequently be sufficient for practical purposes.*

† Permanent-way materials have been tested by Ludwik's cone-pressure method with two objects: to inquire into the suitability of the method for practical purposes, and to ascertain the relation between the cone-pressure hardness and the tensile strength.

The experiments have been conducted in connection with the acceptance tests of the materials supplied to the J. R. Austrian State Railways during the year 1908, in the Trzynietz Iron Works of the Österr. Berg- und Hüttenwerks-Gesellschaft with the aid of an Amsler-Laffon cone-pressure hardness tester‡ on a Mohr and Federhaff testing machine.

The material experimented upon comprised rails, railway ties, splices, and steel crossings.

The specimens were not prepared in any way apart from being cleaned; an exception was made in the case of the steel points, in which the outer skin containing coarse impurities had to be removed completely.

The following are the chief results:

The ratio of tensile strength to cone-pressure hardness had a mean value of about .335, the range of deviation being ± 6 per cent.

The lowest tensile strength of 65 kg./mm.^{2} (42 tons per square inch), admissible for rails, corresponded to a cone-pressure hardness of about 190.

The tensile strengths of ties and of smaller parts for the permanent way varied between 39 and 47 kg./mm.^{2} (24.75 and 29.8 tons per square inch) and the corresponding hardness numbers between 117 and 144. The range of variation is hence approximately the same for the tensile strengths as for the hardness numbers.

Other methods of testing hardness have been used. The sclerometer of Turner makes use of a diamond point which is drawn across the surface to be measured. The weight required upon this point to make a barely visible scratch determines the degree of hardness. This machine is sometimes used with a series of standard weights and the width of a scratch made by one of these

* For instance, the Prussian Railway Department stipulates for rails of a minimum tensile strength of 60 kg./mm.^{2} (38 tons per square inch), with balls of 19 mm. ($\frac{3}{4}$ inch) diameter and 50 tons loads, impression depths of from 3.5 to 5.5 mm.; for rails of a minimum tensile strength of 70 kg./mm.^{2} (44.5 tons per square inch), impression depths ranging from 3 to 5 mm. Breaking tests and ball tests have to be made in equal numbers. (Zentralblatt der Bauver-waltung, 1908, No. 77, p. 520.)

† The Cone-pressure Test for Determining the Hardness of Permanent-way Materials, by Dr. techn. August Geßner, Vienna. International Association for Testing Materials, 5th Congress, Copenhagen, 1909. McGraw-Hill Book Company, New York.

‡ Compare P. Ludwik, " Die Kegelprobe, ein neues Verfahren zur Hartebestimmung von Materialien." Berlin, 1908, Julius Springer.

measured under a microscope. The Keep test employs an instrument which drills into the specimen and gives a measure of the work required to cut out the metal, thus testing not only the surface, but also the interior. The Jaggar instrument is similar, but uses a small diamond drill in connection with a microscope.

Resistance to penetration was long tested by the United States Ordnance Department by means of a weighted punch, and a somewhat similar result was obtained by means of a series of needles of graded hardness, which were tried in succession until one was found that would scratch the material under test.

While many inconsistencies are found in hardness tests, it is generally conceded that the test affords an excellent comparison of metals of the same general composition and treatment, and the results thus far seem to justify the expectation that it will in many cases be possible and advantageous to employ this method in the testing of rails in place of the more elaborate and expensive tensile strength tests which some foreign engineers require in addition to the drop test.

The magnetic laboratory of the Bureau of Standards is carrying on an investigation on the relation between the magnetic and mechanical properties of steels. The reluctance, or the ratio of the magnetizing force to the magnetic induction, of a rail is greatly affected by changes in homogeneity, such as may be caused by segregation, blowholes, or strains due to any cause whatever. By means of the magnetic data taken along the length of a rail it is possible to detect the presence of these defects.

Special machines have been devised from time to time for testing different properties of the rail, as the machine for testing rail wear illustrated in Fig. 151.

* The Pennsylvania Steel Company has a machine (Fig. 214) for testing rail wear which enables specimens of rails to undergo wear similar to that imposed upon them by every description of traffic, but in a much shorter time than if tried in the ordinary road. The rails are fixed to a 20-foot diameter circular frame, three specimens being included in the circle. Two standard 33-inch wheels having independent axles fixed at each end of a heavy casting, which is pivoted at the center of the circle, run upon the rails at speeds up to 85 revolutions per minute, equivalent to a train speed of about 60 miles per hour. There are devices by which, through means of springs, pressure is exerted vertically and also centrifugally on the rail, so that the action of the load can be imitated, as well as that of its lateral pressure on the rail, and the effect produced by continuous wear on the rails of different manufacture and composition can be estimated in a comparatively short time.

* Railway and Engineering Review, Chicago, 1908, Vol. XLVIII, p. 868.

FIG. 214. — Machine for Testing Rail Wear at Pennsylvania Steel Company.

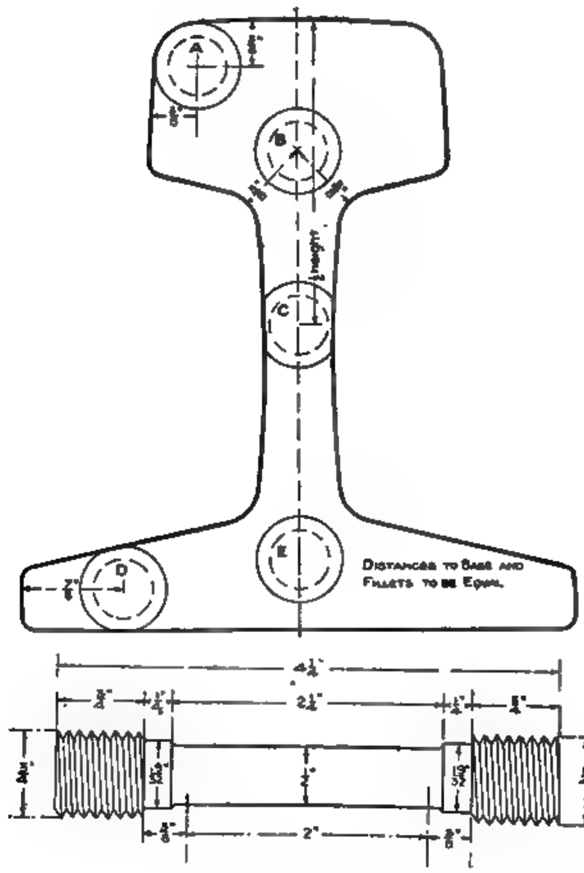


FIG. 215. — Diagram of Round Test Pieces; Tensile Tests on Rail Steel. (Wickhorst.)

Extensive tests have been made of the tensile strength of the steel in the rail by Mr. M. H. Wickhorst, Engineer of Tests of the Rail Committee of the American Railway Engineering Association, covering rails rolled at Gary and at the Lackawanna Steel Company.

The rails from the Gary works were open-hearth steel and 100-pound, A. R. A., Type B section. The ingots furnished six rails, which were lettered *A, B, C, D, E, F*, the *A* rails coming from the top of the ingot, etc.

Tensile tests were made of pieces ½-inch diameter by 2-inch gauge length, cut from near the top end of each rail, as shown in Fig. 215. Five locations in the sections were selected as

shown, and tests were made in duplicate, the bar being cut sufficiently long to make two test pieces. The yield point was determined by means of a Capp's multiplying divider, which method gives a result somewhat above the elastic limit, but which, however, is probably sufficiently definite to make it desirable to determine it, and is not subject to the irregularities of the yield point as determined by the drop of the beam of the test machine, or even by ordinary dividers.

The test pieces were very close to ½-inch diameter at the center, but toward the ends of the gauge length most of them were from .002 to .004 inch larger in diameter. This would tend to make the elongation less than if the diameter were perfectly uniform.

The results of the tensile tests are shown in Table LXXII.

The duplicates agree well with each other except in a few cases where the test pieces broke " short " as follows: One sample from base of the *A* rail, one sample from the interior of the head of the *B* rail, and one sample from the corner of the head of the *C* rail. One sample from the web of the *A* rail should probably also be classed here. The duplicates from the lower rails of the ingot agree particularly well, indicating a freedom from local irregularities. The ratio of the yield point to the tensile strength averages about 51 per cent, and most specimens differ but little from this figure. A comparison of the tensile strength is interesting. Table LXXIII shows the tensile strength of the sample in each pair that gave the greatest ductility.

The *b* samples from the interior of the head and the *c* sample from the web represent what was originally the interior of the ingot, and in the *A* rail these samples show strengths much higher than the samples from the other parts of the section representing what was the outer part of the ingot. This is also true of the *B* rail, but to a less extent, and also of the *C* rail to a slight extent. As we continue down the ingot, however, conditions are reversed, and we find in the *D* rail a little lower strength in the samples from the interior than in the samples representing what was the outer portion of the ingot. This difference is greater in the *E* rail and greatest in the *F* rail.

The *a* sample from the corner of the head and the *d* sample from the flange would be metal of similar chemistry, but the flange has a considerably lower finishing temperature and is also reduced differently. Table LXXIV compares results from these two places.

The *d* sample from the flange of the *A* rail is abnormal, with a low strength and high ductility, being evidently taken at a point of negative segregation of carbon; but, except for this sample, the *d* samples from the flange show a little

TABLE LXXII. — TESTS ON STRENGTH OF RAIL STEEL

Tensile Tests on Open Hearth Rail Steel from Gary (Wickhorst)

Rail.	Location.	Yield Point.	Tensile Strength.	Ratio.	Elongation.	Reduction of Area.
		Pounds per Square Inch.	Pounds per Square Inch.		Per cent in 2 Inches.	Per cent.
A	*a*-head, corner	63,930	124,800	51	10	15
		61,640	125,800	49	9.5	19
	b-head, interior	69,510	134,400	52	8	12
		70,020	133,900	52	9	16
	c-web	....	134,900	....	7	8
		73,060	141,000	52	9	10
	d-flange	65,960	121,700	54	14	26
		65,960	123,300	54	12	21
	e-base	60,890	109,600	....	3.5	2
		56,820	120,200	47	11	19
B	*a*-head, corner	63,420	128,800	49	11.5	20
		65,690	128,300	51	11	19
	b-head, interior	66,970	....	....	1.5	2
		68,220	135,900	50	9	16
	c-web	70,310	137,000	51	11	19
		70,010	137,000	51	9.5	19
	d-flange	66,970	132,900	50	10.5	19
		65,690	129,800	51	12	23
	e base	64,940	129,400	50	10	19
		63,930	126,800	50	10	16
C	*a*-head, corner	67,710	130,900	52	11.5	22
		65,690	....	....	3	3
	b-head, interior	66,970	132,900	50	10	16
		69,230	133,400	52	10	17
	c-web	66,970	133,900	50	11	20
		66,230	133,900	50	11.5	21
	d-flange	66,490	132,900	50	12.5	26
		67,480	133,400	51	12.5	27
	e-base	64,170	128,300	50	10.5	19
		64,170	128,800	50	11	19
D	*a*-head, corner	67,990	132,400	51	12	19
		68,720	130,900	52	11	21
	b-head, interior	64,940	129,300	50	11	16
		65,930	128,300	52	11	21
	c-web	66,930	130,800	51	11	24
		66,970	131,900	51	11.5	23
	d-flange	70,020	133,900	52	13	28
		70,460	134,400	52	12.5	27
	e-base	65,690	130,900	50	10	20
		69,290	132,400	52	10.5	19
E	*a*-head, corner	66,740	127,900	52	11	19
		....	125,300	....	11	19
	b-head, interior	63,920	124,800	51	11	20
		64,180	124,300	52	11	21
	c-web	64,940	128,900	50	12.5	25
		66,460	128,900	52	12	23
	d-flange	67,440	131,800	51	12	26
		68,220	132,400	52	12	25
	e-base	68,220	129,800	53	11	20
		69,510	130,400	53	10.5	19
F	*a*-head, corner	65,210	128,400	51	12	19
		63,420	128,300	50	12	20
	b-head, interior	60,900	120,800	50	12	22
		66,500	123,700	54	12	21
	c-web	64,680	125,300	52	13	25
		64,180	125,800	51	13	25
	d-flange	70,020	132,400	53	11.5	27
		67,710	131,900	51	12.5	21
	e-base	63,670	127,300	50	11	20
		68,950	128,300	54	11	20

TABLE LXXIII.—TESTS ON STRENGTH OF RAIL STEEL

Comparison of Strength in Different Parts of Open Hearth Rails from Gary (Wickhorst)

Rail.	*a*-Head, Corner.	*b*-Head, Interior.	*c*-Web.	*d*-Flange.	*e*-Base.
A	124,800	133,900	141,000	121,700	120,200
B	128,800	135,900	137,000	129,800	129,400
C	130,900	133,400	133,900	133,400	128,800
D	132,400	128,300	131,900	133,900	132,400
E	127,900	124,300	128,900	131,800	129,800
F	128,300	120,800	125,300	131,900	128,300
Average	128,800	129,400	133,000	130,400	128,200

TABLE LXXIV.—TESTS ON STRENGTH OF RAIL STEEL

Comparison of Strength and Ductility of Steel taken from the Corner of the Head and Flange of Open Hearth Rails (Wickhorst)

Rail.	Tensile Strength pounds per Square Inch.		Elongation in 2 Inches.		Reduction of Area.	
	a	*d*	*a*	*d*	*a*	*d*
			Per cent.	Per cent.	Per cent.	Per cent.
A	124,800	121,700	10	14	15	26
B	128,800	129,800	11.5	12	20	23
C	130,900	133,400	11.5	12.5	22	27
D	132,400	133,900	12	13	19	28
E	127,900	131,800	11	12	19	26
F	128,300	131,900	12	12.5	20	21
Average *B* to *F*	129,700	132,200	11.6	12.4	20	25

higher strength and also a little greater ductility. As the difference in the work of rolling is perhaps sufficient to account for this, the conclusion seems to be that the difference in rolling temperature has not resulted in any important difference in the tensile properties.

The *b* sample from the interior of the head and the *c* sample from the web would be of similar chemistry, as representing the interior of the ingot, but the web is thinner and gets more work in rolling and probably is finished at a lower temperature. A comparison of these two locations is shown in Table LXXV.

TABLE LXXV.—TESTS ON STRENGTH ON RAIL STEEL

Comparison of Strength and Ductility of Steel taken from the Interior of the Head and Web of Open Hearth Rails (Wickhorst)

Rail.	Tensile Strength Pounds per Square Inch.		Elongation in 2 Inches.		Reduction of Area.	
	b	*c*	*b*	*c*	*b*	*c*
			Per cent.	Per cent.	Per cent.	Per cent.
A	133,900	141,000	9	9	16	10
B	135,900	137,000	9	11	16	19
C	133,400	133,900	10	11.5	17	21
D	128,300	131,900	11	11.5	21	23
E	124,300	128,900	11	12.5	21	25
F	120,800	125,300	12	13	22	25
Average *B* to *F*	128,500	131,400	10.6	11.9	19.4	22.6

In the *A* rail it is probable that the carbon is higher in the web sample than in the head sample, but in the other rails there probably are no great differences, and the averages shown above are of the *B* to *F* rails inclusive. The tensile strength decreases as we go down the ingot and the ductility increases. The web samples, as compared with the head samples, show a little greater strength, an average of 131,400 pounds, as against 128,500 pounds, and also a little greater ductility, an average elongation of 11.9 per cent, as against 10.6 per cent, and a reduction of area of 22.6 per cent, as against 19.4 per cent. This difference, it would seem, is probably due to the increased work in rolling that the web gets. It is also interesting to note that the top rails show as good ductility in the head samples as the lower rails, allowing, of course, for the difference in tensile strength, which would make about 3 per cent decrease in elongation for an increase in tensile strength of 10,000 pounds.

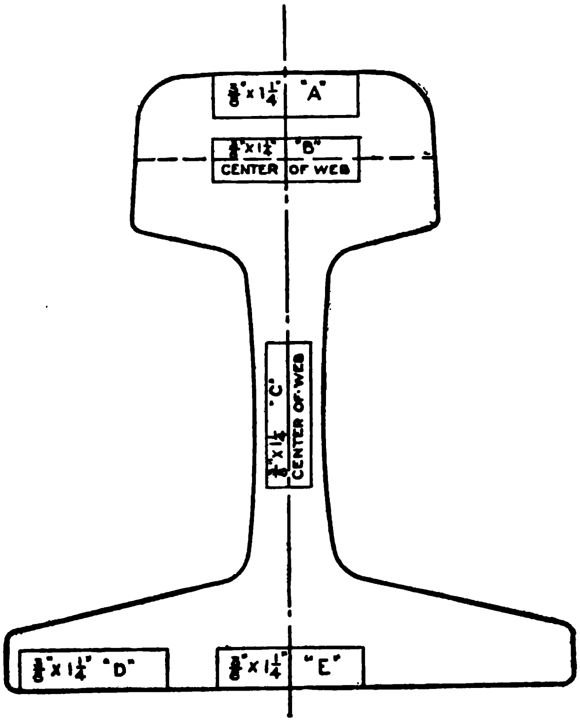


FIG. 216. — Test Pieces 16 inches long. Diagram of Flat Test Pieces. Tensile Tests on Rail Steel. (Wickhorst.)

The tensile tests on the rail steel from the Lackawanna mill were from titanium Bessemer rails, 90-pound, A. R. A., Type B.

It was planned to make tensile tests of pieces from near the top ends of each rail by cutting five flat pieces $\frac{3}{8}$ by $1\frac{1}{4}$ by 16 inches from each rail as shown in Fig. 216. The test pieces were cut in this manner from the *A* and *D* rails, but it soon appeared that the time required to prepare the pieces in this manner would cause considerable delays, and then, too, the surfaces are apt to be finished in a condition unsatisfactory for test. The plan was then changed so as to obtain pieces $\frac{1}{2}$ inch in diameter and 2-inch gauge length, as shown by Fig. 215. The pieces from the *B* and *C* rails were prepared in this manner. The results of the tensile tests are shown in Table LXXVI. Care must be taken not to compare the results of the flat test pieces with those from the round test pieces, except, perhaps, as regards the tensile strength, although even here the shape of the test piece would make some difference.

TABLE LXXVI.—TESTS ON STRENGTH OF RAIL STEEL

Tensile Tests on Titanium Bessemer Rail Steel from Lackawanna (Wickhorst)

Rail.	Location.	Kind of Test Piece.	Tensile Strength.	Elongation.	Reduction of Area.
			Per Square Inch.		
A	*a*-head	Flat	103,400	15.5 in 8 inches	23 flat
	b-head	"	111,100	20.0 " 8 "	16 "
	c-web	"	109,200	14.5 " 8 "	18 "
	d-flange	"	103,300	11.7 " 8 "	19 "
	e-base	"	105,000	13.7 " 8 "	21 "
B	*a*-head	Round	111,700	19.0 " 2 "	29 round
	b-head	"	122,900	14.0 " 2 "	20 "
	c-web	"	116,200	17.5 " 2 "	27 "
	d-flange	"	110,700	19.0 " 2 "	31 "
	e-base	"	111,600	18.0 " 2 "	33 "
C	*a*-head	"	109,100	20.0 " 2 "	36 "
	b-head	"	112,100	16.0 " 2 "	25 "
	c-web	"	112,300	21.0 " 2 "	37 "
	d-flange	"	109,600	20.0 " 2 "	34 "
	e-base	"	112,400	19.5 " 2 "	33 "
D	*a*-head	Flat	109,800	12.5 " 8 "	17 flat
	b-head	"	106,800	10.0 " 8 "	12 "
	c-web	"	104,700	13.7 " 8 "	23 "
	d-flange	"	108,600	10.0 " 8 "	21 "
	e-base	"	110,000	9.5 " 8 "	16 "

The following is a record of tensile tests made by Waterhouse* on 100-pound A. S. C. E. rail taken from stock. The steel was made by the acid Bessemer process and the ingots rolled without reheating. From this rail two adjacent pieces 8¾ inches long were cut with a slow-speed cold saw, and from these pieces tensile-test bars were machined in the positions shown in Fig. 217. The results of the tensile tests are given in the following table, the figures being the average of those obtained from the duplicate pieces:

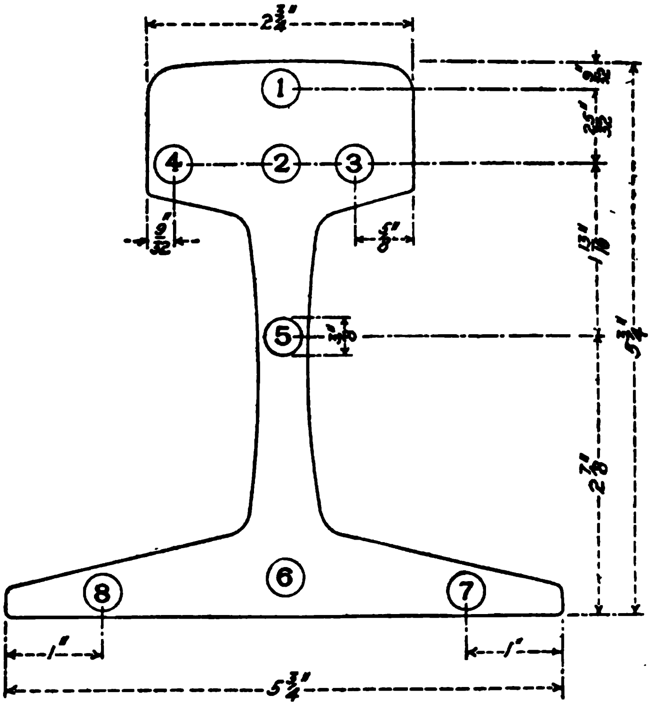


FIG. 217. — Location and Numbers of Test Pieces used in Waterhouse's Tests. (Railroad Age Gazette.)

* Examination of 100-pound Rails. G. B. Waterhouse. Railroad Age Gazette, July 10, 1908, p. 478.

TABLE LXXVII.—TESTS ON STRENGTH OF RAIL STEEL

Tensile Tests on Bessemer Rail Steel (Waterhouse)

	Elastic Limit.	Ultimate Stress.	Elongation in 2 Inches.	Reduction of Area.
	Pounds.	Pounds.	Per cent.	Per cent.
1............	52,200	108,400	16.75	29.9
2............	52,200	109,850	16.25	28.4
3............	54,460	110,750	18.50	33.2
4............	55,000	110,150	18.50	28.6
5............	53,100	110,300	18.25	29.4
6............	53,820	110,400	18.00	31.0
7............	51,740	109,850	18.25	35.4
8............	53,340	111,300	17.00	36.4

Table LXXVIII shows the chemical composition of the rails tested in the three tests just mentioned.

TABLE LXXVIII.—CHEMICAL COMPOSITION OF RAIL STEEL IN TENSILE TESTS OF WICKHORST AND WATERHOUSE

	Wickhorst.		Waterhouse.
	Gary.	Lackawanna.	
	Per cent.	Per cent.	Per cent.
Carbon..................	0.72	0.48	0.51
Silicon..................	0.20	0.14	0.147
Manganese	0.72	0.90	0.77
Sulphur..................	0.036	0.040	0.078
Phosphorus..............	0.036	0.091	0.089
Copper..................	....	....	0.185

28. The Strength of the Rail and Proper Weight for Various Conditions of Loading

In determining the proper stress to use for the rail, careful consideration must be given to the exact meaning of the terms by which the strength of the steel is shown.

* The elastic limit or yield point may be properly called the limit of proportionality of stress to deformation, or more briefly, the limit of proportionality. The limit of proportionality is sometimes called the "true" elastic limit, and is frequently regarded as a measure of the load-carrying capacity of a member or structure.

The absolute value of this limit cannot, in general, be determined even by the most careful measurements of deformation and load. It has been the experience of experimenters that any additional refinement of measurements in stress-deformation tests results in the detection of the limit of proportionality

* Proceedings American Society for Testing Materials, 1910, Vol. X, pp. 243, 244. Moore.

at a stress lower than that determined by the less refined methods of measurement. Perhaps the thermo-electric apparatus used by Turner * and Rasch † for measuring deformation is the most delicate yet employed, and both of these experimenters showed the existence of a limit of proportionality at stresses far lower than those determined by extensometer measurements as ordinarily made.

Members and structures become more and more nearly perfectly elastic if subjected to repeated stresses in the same direction, even if these stresses are so far beyond the limit of proportionality that there is a small but well-defined permanent set upon release of the load. Fig. 218 shows the result of loading a beam several times to a stress well beyond the elastic limit. The first load applied to the beam produced considerable permanent set, and during the application and release of load considerable energy was lost, presumably in heat. This energy is shown by the shaded area to the left of the figure. During the second cycle of loading and release much less energy was lost, as shown by the central shaded area; and during the third cycle the beam behaved as if almost perfectly elastic. It should be noted that the above results would not be obtained if the direction of the load were reversed.

One Division = 0.1 in: Deflection

FIG. 218. — Effect of Repeated Loads on Beams. (Am. Soc. for Testing Materials — Moore.)

The ultimate strength, or maximum capacity for resisting stress, has a ratio to the maximum stress due to the working load, which, although less in metal than in wooden or stone structures, is, nevertheless, made of considerable magnitude in many cases. It is much greater under moving than under steady "dead" loads, and varies with the character of the material used. For machinery it is usually 6 or 8; for structures erected by the civil engineer, from 5 to 6.‡

In general, parts of structures are so proportioned as to carry their loads without risk of exceeding their elastic limits; and in such cases the factor of safety should probably always be referred to the elastic limit.

* Thermo Electric Measurements of Stress, Transactions American Society of Civil Engineers, Vol. XXVIII, January, 1902, p. 27.

† Proceedings International Association for Testing Materials, No. 11, August 4, 1909, Article VII.

‡ Iron and Steel, Materials of Engineering, Thurston, 1909, p. 340.

The elastic limit is made the basis of estimates by nearly all French engineers, while the ultimate strength is taken by German engineers, using a factor of safety of larger magnitude. British and American engineers usually base all calculations on the ultimate strength, although the former system is extending in general practice, and the limit of working load is made to fall well within the limit of elasticity.

The general practice at the present time, for railway and highway bridges, is to use a unit strain of about one-half the elastic limit of the material. This factor is considered correct in places where the load assumed is an absolute maximum, as, for instance, where it consists of a definitely determined dead load only.

In the rail the maximum stress acts during a very short space of time and its effect is not the same as the same load applied for a longer period. It is possible to apply a much greater stress than the elastic limit of the metal, provided the stress be applied very quickly and then released.

The excellent service given by some of the rails of lighter section, exposed to heavy wheel loads, gives evidence that a limited number of excessive stresses in the rail will not cause injury when applied for the small fraction of a second, as is the case of the stress caused by the wheel load.

An extreme fiber stress of 20,000 pounds per square inch as applied to the base of the rail probably represents a satisfactory mean between the danger, on the one hand, of not providing a sufficient margin of safety for the unknown quantities of the problem and the liability, on the other hand, of taking too great a factor of safety, and thus designing an uneconomical structure.

The following remarks of Professor Unwin are pertinent to this question:

"If an engineer builds a structure which breaks, that is a mischief, but one of a limited and isolated kind, and the accident itself forces him to avoid a repetition of the blunder. But an engineer who from deficiency of scientific knowledge builds structures which don't break down, but which stand, and in which the material is clumsily wasted, commits blunders of a most insidious kind."

Any consideration of the strength of the rail should take account not only of the stresses in the rail itself and the ability of the material of which it is composed to resist them, but a proper proportion must be made of the rail in order that it may distribute the wheel load to the ties in such a manner as not to overstrain any part of the track structure. The fact that a rail will not break should not be the determining factor in its selection, if, on account of lack of stiffness, it will allow too great a proportion of the load to come on a tie.

The damaging effects of overloading the track, while much less apparent than the results attending the use of too great loads in other engineering structures, are, nevertheless, of very real importance, and the lack of proper appreciation of the fundamental principles underlying its design has brought about

conditions requiring excessive maintenance charges to keep the track in proper condition.

As the real function of the heavier rails is to distribute the wheel load and prevent too great a concentration of pressure on the track substructure, we have two limiting conditions to consider: First, the rail should be stiff enough to enable it to transfer the load in such a manner as not to exceed the maximum bearing power of the track substructure, and second, the safe working stress of the metal in the rail must not be exceeded.

Before investigating the proper weight of rail to use with any track structure, the weight and types of the locomotives and cars to be run over it should be considered, and the maximum wheel pressures ascertained for each type.

The bearing power of the roadway or subgrade should next be examined. The influence of the character of the roadway is well shown by the following case reported by Mr. A. G. Wells, General Manager of the Atchison, Topeka and Santa Fe:*

"From Seligman to Barstow our track is laid with eighty-five-pound rails; the density of the traffic is practically the same over every foot of it. Between Yucca and Barstow, a distance of 227 miles, the subgrade is sandy, porous, and well drained; between Yucca and Seligman, a distance of 91 miles, the subgrade is largely clay, of a kind that holds water. From November, 1907, to October, 1908, we had eighty-three rail breakages on the territory first named, or a percentage of .001; on the other stretch we had in the same period seventy-two breakages, the percentage being .0025, or, in other words, where the subgrade was dense and more or less clay, the breakages per mile were two and one-half times greater than where the subgrade was sandy."

The bearing power of the subgrade is such an important factor in proportioning the track that it will prove profitable to examine what takes place when the soil is subjected to pressure.†

As in any structure, good judgment must enter into the design; the formulæ which will be demonstrated must be used as guides only. These formulæ will depend upon the angle of repose of a homogeneous granular mass. For ordinary earths for which the angles of repose are known, the results obtained by the use of the formulæ will compare very favorably with those obtained from examples of the best practice.

When the angle of repose is not known it should be determined by test.‡

* Railroad Age Gazette, April 9, 1909.

† The following discussion is based upon Retaining Walls for Earth, Howe, New York, 1896.

‡ This can conveniently be done by measuring the force required to cause slipping of two portions of the earth past each other when subjected to a known pressure, and

$$\tan \phi = \frac{s}{p}.$$

where ϕ = angle of repose.
s = force required to cause slipping.
p = pressure on earth.

Earth which has an angle of repose of at least 27 degrees may be considered as firm. From Table LXXIX it is seen that sand, gravel, and damp clay are classed as firm soils; however, these may become so saturated with water that their angles of repose will become considerably less than 27 degrees, hence precaution must be taken against too much water by draining the ground in the immediate vicinity of the roadbed. Particular care must be taken in the case of clay, or sand which will become a kind of quicksand when saturated with water.

The water which destroys the bearing power of such soils may come from below by capillary attraction,* and the drainage should be carried to a depth sufficient to prevent this. Semi-fluid soils, such as quicksand, alluvium, etc., should be removed where practicable or the foundation carried to a lower stratum.

TABLE LXXIX. — ANGLES AND COEFFICIENTS OF FRICTION

(Rankine's Applied Mechanics.)

	$\tan \phi$.	ϕ.	$\frac{1}{\tan \phi}$
		Degrees.	
Earth on earth	0.25 to 1.0	14 to 45	4 to 1
Earth on earth, dry sand, clay, and mixed earth	0.38 to 0.75	21 to 37	2.63 to 1.33
Earth on earth, damp clay	1.0	45	1
Earth on earth, wet clay	0.31	17	3.23
Earth on earth, shingle, and gravel	0.81	39 to 48	1.23 to 0.9

Let Fig. 219 represent a section of the track, and

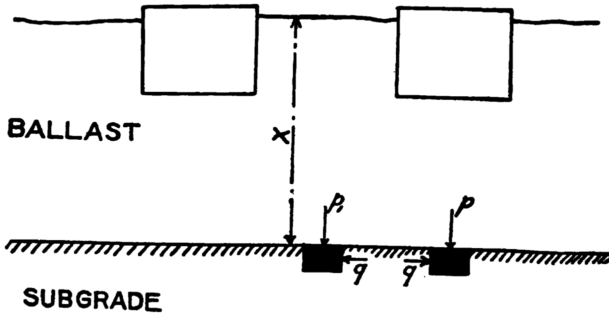


Fig. 219. — Resistance of Sub-grade to Pressure of the Track.

x = the depth of ballast;

p = the maximum supporting power per square foot of the subgrade;

p_1 · the pressure exerted on subgrade midway between ties;

γ = the weight of one cubic foot of ballast;

ϕ = the angle of repose of subgrade;

$x\gamma$ equals the vertical intensity of the pressure caused by the weight of the

* Movements of Ground Water, by F. H. King and C. S. Slichter, Government Printing Office, Washington, D. C., 1899, p. 65.

ballast on the subgrade midway between the ties. This pressure is augmented by the pressure transmitted from the tie, and, while this is much less between the ties than immediately underneath a tie, it is, nevertheless, an important factor in strengthening the surface of the roadbed.

If we assume this extra pressure on the roadbed midway between the ties to equal in amount γx we will probably be on the safe side and can then write

$$p_1 = 2\,\bar{\gamma x}.^*$$

Now when the ballast is about to sink

$$\frac{p}{q} = \frac{1+\sin\phi}{1-\sin\phi} \quad \text{or} \quad q = p\,\frac{1-\sin\phi}{1+\sin\phi}.$$

But when the roadbed under the tie is on the point of sinking, the part of the roadbed between the ties must be on the point of rising, or

$$\frac{q}{p_1} = \frac{1+\sin\phi}{1-\sin\phi},$$

and the supporting power of the subgrade, or

$$p = p_1\left\{\frac{1+\sin\phi}{1-\sin\phi}\right\}^2 = 2\,\gamma x\left\{\frac{1+\sin\phi}{1-\sin\phi}\right\}^2.$$

For convenience the values $\left\{\frac{1+\sin\phi}{1-\sin\phi}\right\}^2$ are given in Table LXXX and for γ in Table LXXXI.

TABLE LXXX

Values of $\left\{\frac{1+\sin\phi}{1-\sin\phi}\right\}^2$

(Howe.)

ϕ.	$\left\{\frac{1+\sin\phi}{1-\sin\phi}\right\}^2$.	ϕ.	$\left\{\frac{1+\sin\phi}{1-\sin\phi}\right\}^2$.
0	1.00	23	5.21
5	1.42	24	5.62
6	1.52	25	6.07
7	1.63	26	6.56
8	1.75	27	7.09
9	1.88	28	7.67
10	2.02	29	8.30
11	2.16	30	9.00
12	2.32	31	9.76
13	2.50	32	10.59
14	2.68	33	11.50
15	2.88	34	12.51
16	3.10	35	13.62
17	3.33	36	14.84
18	3.59	37	16.18
19	3.86	38	17.67
20	4.22	39	19.64
21	4.48	40	21.16
22	4.83		

* This apparently would be a safe assumption for a depth of gravel ballast under the tie of 18 inches and 12 inches of stone. For a less depth of ballast the pressure would be less and for a greater depth the pressure would increase, the increase being more rapid in the case of the stone than of the gravel ballast.

TABLE LXXXI. — VALUES OF γ

Name of Ballast.	Average Weight, in Pounds per Cubic Foot.
Gravel	90 to 106
Sand	90 to 106
Sand perfectly wet	118 to 129
Stone, crushed	90 to 108

Considering first the weight of rail which will give a proper distribution of pressure to the track, we may adopt a tentative system of classification for the track structure based upon the kind of tie, tie spacing, depth and kind of ballast, and character of subgrade. As previously noted, a tie spacing of 20 inches with 18 inches of gravel or 12 inches of stone under the tie, resting on a roadbed capable of bearing 1.5 tons per square foot, will sustain safely a load of 700 pounds per linear inch under each rail. This grade of track we will designate as class *A*.

Class *B* and *C* will represent weaker structures, which may be brought about by a departure in any or all of the elements from those found in class *A* track.

A track would be graded as class *B* if it was capable of carrying only 600 pounds per linear inch under each rail. This might occur in several ways. A tie spacing of 22 inches, but with all the other elements of class *A* track, would diminish the strength of the structure on account of greater concentration of the load on each tie and on the subgrade; similarly, a lesser depth of ballast would affect the load on the subgrade. Evidently, a track with all the other elements of class *A*, but resting on a soil having a lower bearing power, would offer less resistance to the action of the wheel load.

Table LXXXII presents descriptions of different kinds of track in each of these classes. It will be observed that the limiting factors may be considered as being the supporting power of the roadbed and the bearing of the rail on the tie. The bending stress in the tie and the bearing of the tie on the ballast are of secondary importance.

Considering first the bearing under the rail. This is evidently a function of the tie spacing and kind of wood of which the tie is made. For class *A* track, capable of supporting 700 pounds per linear inch under each rail, a tie spacing of 20 inches would give a load on each tie under the rail bearing of 14,000 pounds. This is about the limit of the strength of the woods shown for class *A* track, and therefore excludes the use of weaker woods or greater tie spacing for this class of track.

In class B track, having a supporting power of 600 pounds per linear inch under each rail, the tie spacing may be increased to 22 inches for the woods allowed in class A track. It is doubtful whether the group of woods shown in the table under class C track should be used for class B track even with a tie spacing of 20 inches.

TABLE LXXXII. — CLASSES OF TRACK

Class of Track.	Tie.			Ballast, Depth under Tie.		Subgrade Bearing Power.	Bearing Power of Track under Each Rail.
	Size.	Class of Woods Represented by	Spacing c. to c.	Stone.	Gravel.		
	Inches.		Inches.	Inches.	Inches.	Tons per Square Foot.	Pounds per Linear Inch.
A_1	7×9	Oak, locust, hard maple, hickory, cherry; not tie plated.	20	12	18	1.0 to 1.5	700
A_2	7×9	Longleaf pine, black walnut, beech, birch, elm, gum, hemlock, Douglas fir; tie plated.	20	12	18	1.0 to 1.5	700
B_1	7×8	Same as classes A_1 and A_2	22	12	18	1.0 to 1.5	600
B_2	7×8	Same as classes A_1 and A_2	20	9	14	1.0 to 1.5	600
B_3	7×8	Same as classes A_1 and A_2	20	12	18	0.8 to 1.2	600
C_1	7×8	Loblolly pine, shortleaf pine (at times this wood is nearly equal to longleaf), soft maple, catalpa, chestnut, white pine, Norway pine; tie plated.	22	6	10	1.0 to 1.5	450
C_2	7×8	Do	22	12	18	0.5 to 1.0	450
C_3	7×8	Do	20	8	12	0.5 to 1.0	450

The low-supporting power of class C track permits the use of weaker woods. A 22-inch tie spacing for this grade of track gives a load at the rail bearing of about 10,000 pounds.

The pressure transmitted to the subgrade is determined by the spacing of the ties (or more properly by the distance between adjacent ties) and the depth and kind of ballast used. In the table three characters of subgrade are considered, the firmest having a bearing power of from 1.0 to 1.5 tons per square foot and the least firm a bearing power of from 0.5 to 1.0 tons per square foot.

By applying the formula

$$p = 2\,\gamma x \left\{\frac{1 + \sin\phi}{1 - \sin\phi}\right\}^2$$

we see that the firmer grade corresponds to a soil with an angle of repose of from 23 degrees to 31 degrees for 12 inches of stone ballast or 18 inches of gravel ballast under the tie, and from 28 degrees to 36 degrees with 6 inches of stone or 10 inches of gravel ballast under the tie. Table LXXIX shows that these angles of repose fall within the limits given for dry sand, clay, and mixed earth.

The subgrade, having a supporting power of 0.5 ton per square foot, corresponds to a soil having angles of repose varying from 13 degrees to 20 degrees under the conditions stated in the table. This agrees with the angle of repose for wet clay shown in Table LXXIX.

Table XLVII (article 19) gives, for a subgrade capable of bearing 1.5 tons per square foot, an allowable load applied to the tie at the rail bearing of from 10,100 to 11,800 pounds, for the size of tie, depth and kind of ballast used in class A track. Owing to the rapid application of the load it has been assumed in article 19 that these values could be safely increased to 14,000 pounds on account of the inertia of the track and roadbed. For 20-inch tie spacing this gives a supporting power of 700 pounds per linear inch of rail.

For the track designated by B_1 in Table LXXXII, owing to the increase in distance between adjacent ties this value falls to 600 pounds per linear inch of rail. In class B_2 track we find from equations Nos. 1 and 2, article 18, that the allowable load at the rail bearing, as determined by a supporting power of 1.5 tons per square foot on the roadbed, is 9500 pounds in the case of 9 inches of stone under the tie and 8500 pounds for 14 inches of gravel. Making the same allowance for the inertia of the roadbed, as in the previous case, it is seen that a supporting power of about 600 pounds per linear inch of rail is realized.

In class B_3 track, if we take the supporting power of the roadbed as 1.2 tons per square foot, we find values from 7700 to 9000 pounds for the load that can be applied to the tie at the rail bearing, which agree fairly well with those previously determined for class B_2 track.

The bearing power under each rail, as determined by the permissible load on the roadbed for class C track, has been calculated in a similar manner.

It will be noticed that in each case the upper limits of the bearing power of the roadbed have been worked to in determining the values given in the table. This is a feature of the analysis which requires careful consideration of the kind and volume of traffic over the track.

The inertia of the roadbed plays an important part in strengthening the track when the maximum loads imposed upon it do not occur too frequently, as in the case of high-speed passenger trains where the most destructive forces to be provided for are those produced by the drivers of the locomotive. In the case of dense freight traffic where the heavy loads imposed by the engine drivers are followed by the passage of a long train, thus subjecting the track to a continuing load lasting over a considerable interval of time, the inertia of the roadbed is, in a great measure, overcome and a correspondingly lower value for the allowable pressure on the roadbed must be used.

The all steel 70-ton coal cars, which are coming into use on some of the large coal-carrying roads in the East, weigh over 50,000 pounds, and have a capacity of 140,000 pounds. This weight is carried on four axles and a train composed of these cars would prove very destructive to the roadbed unless an ample provision was made for the effect of the repeated application of the heavy wheel loads.

Examining now the weights of rail required to distribute the wheel loads so as not to exceed the bearing power of the track. Table LXXXIII shows the moments of inertia of standard rails*; evidently the rails with the highest moment of inertia will give the most favorable loading of the track structure.

TABLE LXXXIII. — MOMENTS OF INERTIA AND SECTION MODULI OF STANDARD RAIL SECTIONS.

Section.	Weight, Pounds per Yard.	Moment of Inertia.	Section Modulus of Base.
A.S.C.E.	100	43.8	16.11
A.S.C.E.	85	30.0	12.00
A.S.C.E.	75	22.8	9.62
A.R.A. type A	100	48.9	17.78
A.R.A. type A	80	28.8	12.46
A.R.A. type B	100	41.3	15.74
A.R.A. type B	80	25.1	11.08
P.S., Pennsylvania R. R. System	100	41.9	15.91
P.S., Pennsylvania R. R. System	85	29.1	12.02
P.R.R., Pennsylvania R. R.	100	38.0	14.29
P.R.R., Pennsylvania R. R.	85	27.4	11.25
Dudley, New York Central Lines	100	49.0	17.00
Dudley, C. R. R. of N. J.	85	30.4	11.76
Dudley, New York Central Lines	80	28.5	11.53

In Plate XXVI are given the dynamic wheel loads with different axle spacing for rails having moments of inertia of 20, 30, 40, and 50. The curves shown on the diagrams are calculated by the method explained in the first part of article 23 and show the allowable dynamic axle loads, as determined by the safe bearing power of the different classes of track given in Table LXXXII.

An examination of these diagrams shows that for each class of track the allowable wheel load increases with the axle spacing up to a certain point when a maximum is reached and, as the spacing of the wheels is still further increased, the allowable wheel load decreases. The most favorable axle spacing, as might be expected, is greater for the heavier rails than for those of lighter section.

* If the moment of inertia of the section is not known it may be calculated by one of the following methods:

Culmann, C. Centralellipse und kerneines schienenprofils, 5 p. Ill., 1875. (In his Die graphische statik, ed. 2, p. 475.)

Morely, Arthur. Graphical determination of moments, centroids, and moments of inertia of areas, 6 p. Ill., 1908. (In his Strength of Materials, p. 117.)

Sankey, C. E. P. Note on the graphical determination of moments of inertia, 1000 w. dr., 1910. (In Engineer, London, v. 110, p. 57.)

Plate XXVII presents diagrams showing the maximum bending moments in the rails under the conditions given in Plate XXVI. In the table shown on Plate XXVII are given bending moments corresponding to an extreme fiber stress of 20,000 pounds per square inch in the base of the rail. In using this table it should be borne in mind that the relation between the moment of inertia and section modulus of different sections vary. The values given in the table represent average conditions.

A comparison of Plates XXVI and XXVII shows that the wheel load is determined by the bearing power of the track in the case of classes B and C track, but with class A track the working stress of the steel may be exceeded without overloading the track. The dotted lines in the diagram for class A track on Plate XXVI show the correction necessary to apply to the curves of this diagram in order to keep within the working stress of the metal of the rail.

Plate XXVI will now serve as a basis for determining the dynamic wheel load corresponding to any section of rail and axle spacing. For a wheel arrangement consisting of a series of wheels having the same spacing and each supporting approximately the same load, the values of the load may be read directly from the diagrams. This loading satisfies the condition of the calculations which assumes that the tangents to the elastic curve of the rail under the wheels and midway between them are horizontal.

When the wheel spacing is not the same for adjacent wheels, the average of the loads given for each axle spacing should be taken.

In the case of the front and back drivers the conditions are more complex. Here we may have a trailing truck and either a two-wheel or four-wheel leading truck carrying loads much less than those on the drivers. The preparation of charts for all of these conditions and for the case where the wheel spacing of adjacent drivers is not uniform would appear to be a refinement which would not be warranted by the data upon which the calculations must necessarily be based.

It will be observed that little variation in the wheel load occurs after a distance between adjacent wheels of 180 inches is reached, the curve becoming, in most cases, nearly horizontal at this point. In other words the wheels are so far apart as to have little or no effect upon each other.

The following formula is proposed to be used in determining the wheel loads on the front and rear drivers, it is also applicable to the outside wheels of the trucks under the cars.

$$W = \frac{W'}{2} + \frac{W'' - W'''}{2} \cdot \frac{L}{W''} + \frac{W'''}{2}$$

where

W = dynamic load of outside driver.

W' = dynamic load corresponding to the wheel spacing between the outside and adjacent driver.

W'' = dynamic load corresponding to the distance between the outside driver and the center of truck.

W''' = the value given below for different moments of inertia and classes of track.

L = dynamic load on truck wheels (one side).

Moment of Inertia of Rail.	For Front Drivers. Class of Track.			For Back Drivers. Class of Track.		
	A.	*B.*	*C.*	*A.*	*B.*	*C.*
50	36,000	28,000	18,000	40,000	32,000	20,000
40	30,000	26.000	16,000	34,000	30,000	18,000
30	26,000	24,000	14,000	30,000	28,000	16,000
20	....	22,000	12,000	....	26,000	14,000

The term $\frac{W'}{2}$ in the formula represents the part of the driving-wheel load which is supported within the driving-wheel base; $\frac{W'''}{2}$ the load carried by the rail outside of the driving-wheel base if there is no leading truck, this is made smaller than indicated by the diagrams of Plate XXVI in the case of the leading driver on account of the probable extra stress set up in the rail when it is first depressed by the weight of the locomotive.

The term $\frac{W'' - W'''}{2} \cdot \frac{L}{W''}$ is introduced to provide for the extra support afforded by the truck wheels. In the extreme case where $W'' = L$, the wheels ahead of the driver exert the pressure corresponding to their distance from the driver, and the term $\frac{W'''}{2}$ drops out of the equation. When $L = 0$ or there is no leading truck the term $\frac{W'' - W'''}{2} \cdot \frac{L}{W''}$ becomes equal to zero.

The dynamic wheel loads, having been determined, the corresponding static loading can be readily computed by the methods given in article 10 for steam locomotives, article 11 for electric locomotives, and article 12 for cars.

Plate XXVIII presents diagrams showing approximately the static loading that can be placed on the rail with different wheel arrangements. From these diagrams can be obtained the weight of rail and design of track necessary to use in connection with engines where the maximum axle load is fixed, or the diagrams

may be used in determining whether or not it is safe to run a certain weight of equipment over an existing line.

On account of the variation in design of engines a separate examination should be made in most cases, as the diagrams, of necessity, represent general conditions which may be varied from in a considerable degree.

Fig. A, Plate XXVIII, gives the track diagrams for passenger engines of the Atlantic and Pacific types. The main driver in the wheel arrangement of the Pacific engine can carry more weight than when it is one of the outside wheels, as in the case of the Atlantic engine, and for this reason the former engine is generally the most favorable on the track.

The ten-wheel engine is used extensively for passenger and freight service on branch lines. This engine does not have the trailing truck of the two former types, and the rear driver has, therefore, less carrying power than in the Pacific engine, although about the same as the Atlantic where the effect of the trailing truck is offset by the fact that the rear driver is the main wheel. The diagrams given on Fig. B, Plate XXVIII, show the axle loads of ten-wheel engines for classes B and C track.

Fig. C shows diagrams for Mogul and Consolidation freight engines. The wheel arrangement of these engines is quite similar to that of the ten-wheel engine, and it will be found that the curves agree very closely with that of the ten-wheel engine used in freight service.

On Figs. D and E are diagrams for cars. It should again be observed that these smaller diameter wheels should not be loaded as heavily as the drivers, and the diagrams for the loads on car axles are not extended beyond axle loads of 45,000 pounds.

The diagrams of the figures on Plate XXVIII illustrate very clearly the effect of the different wheels on the track, and emphasize the fact that the entire wheel arrangement must be considered in determining the maximum load on any one wheel.

The assumption made by most foreign writers on this subject, that the strains produced by the loads are independent of the position of the wheel is obviously incorrect, as has been shown experimentally by Dr. Dudley's stremmatograph tests.

The diagrams of Plate XXVIII are not extended beyond 60,000 pound axle loads for drivers or 45,000 pounds for car wheels. With carbon steel rails the use of very heavy loads should be approached cautiously until further evidence is obtained in regard to the effect of such wheel loads on the intensity of the stress at the contact of the wheel and the rail. While axle

loads of nearly 70,000 pounds are in service on experimental locomotives, they have not been used in sufficient numbers to demonstrate fully their effect on the rail.

The lack of proper experimental data presents many difficulties in accurately determining the functions performed by the rail. Within certain limits, however, the duty of the rail can be calculated with a considerable degree of accuracy and more attention should undoubtedly be given to the effect of different loadings on the rail in the design of the engines and cars which run over it.

It must be constantly borne in mind in dealing with the design of the track that in many cases the strength of the rail is not the first consideration in the selection of the section to be used, and that the question of obtaining a rail of the requisite stiffness is of the greatest importance. The sudden failure of any part of the track is not to be anticipated within the limits of customary practice, but rapid deterioration of the structure may take place which will eventually result in failure.

Economy of train service has become so important that it is safe to say that there will be no return to lighter loads the tendency is, and will be constantly, in the opposite direction. The importance therefore of giving to the design of the track the same careful investigation as is considered essential in the design of a bridge cannot be over-estimated. The track is, in fact, a continuous girder connecting termini over which pass the same loads as over the bridges.

The discussion of stresses in the ties, ballast and subgrade which has been made in the preceding pages while sufficient to enable the allowable bearing power of the supports of the rail to be determined within reasonable limits, is far from exhaustive enough in its character to serve as a basis for the general design of the track and the proper proportioning of all the elements entering into its construction. Such an analysis would be clearly outside the limits of the present work and while the various tables and formulæ that have been developed appear sufficient for the purpose intended, any general conclusions based upon their evidence alone should be avoided.

CHAPTER VI

INFLUENCE OF DETAIL OF MANUFACTURE

THE evidence of the failure of rails of heavy section rolled within the last few years, equaling and at times exceeding that of lighter rails of earlier manufacture exposed to similar conditions of traffic and roadbed, points unmistakably to defective material in some of the later rails. These rails apparently do not fail in the majority of cases due to too great a stress of the metal, and it is this irregular failure of individual rails due to defects in manufacture which has given rise to such just feelings of dissatisfaction and alarm.

Inferior quality of the metal in the rail may be attributed to two causes: first, the use of imperfect methods of manufacture; second, the influence of the form of the section upon the detail of manufacture.

First, let us examine the methods employed in the manufacture of the earlier rails, which gave such satisfactory results, and which have been so constantly presented to rail makers as representing that which they ought to do.

* The first steel rails were rolled in mills which had been designed for iron rails. Other rolls were used and the number of passes was increased, making the reduction very gradual. All blooms were allowed to cool before being charged into the reheating furnace. After the drawing of one heat and before the charging of another, the furnace was cooled down, then the heat was brought up very gradually and plenty of time was taken to allow the steel to "soak." In the converting house, all the possible practices of crucible steel teeming were introduced. The ingot molds were carefully brushed out, heated and smoked before being used. When the steel was teemed all doors and windows of the casting house were closed and time was not spared on any of the details. It was expected to produce but 50 per cent as much steel as iron rail, and all employees working by the ton were paid twice as much for steel as iron. The constant demand for cheaper prices (Fig. 220) and increased tonnage rapidly changed these conditions.

Many of these practices, it is felt to-day, were entirely without reason, and it is difficult to say as a general proposition that the steel produced was better than is

* See paper on Steel Rails, and Specifications for Their Manufacture, R. W. Hunt. Trans. American Institute of Mining Engineers, Vol. XVII (1888–89), p. 226.

obtainable at the present time. Mr. Buffington stated positively to the Indiana Railway Commission, at its hearing, that the quality of the metal is to-day much better than it ever was before, owing to the increased knowledge and better machines and mechanical appliances than formerly existed.

Mr. James E. Howard, in his report of the accident on the Great Northern Railway, near Sharon, N. D., on December 30, 1911, states: "It is important to consider whether an improvement in the structural condition of rail steel is attainable. Such seems to be the case, since experimental rollings have furnished rails

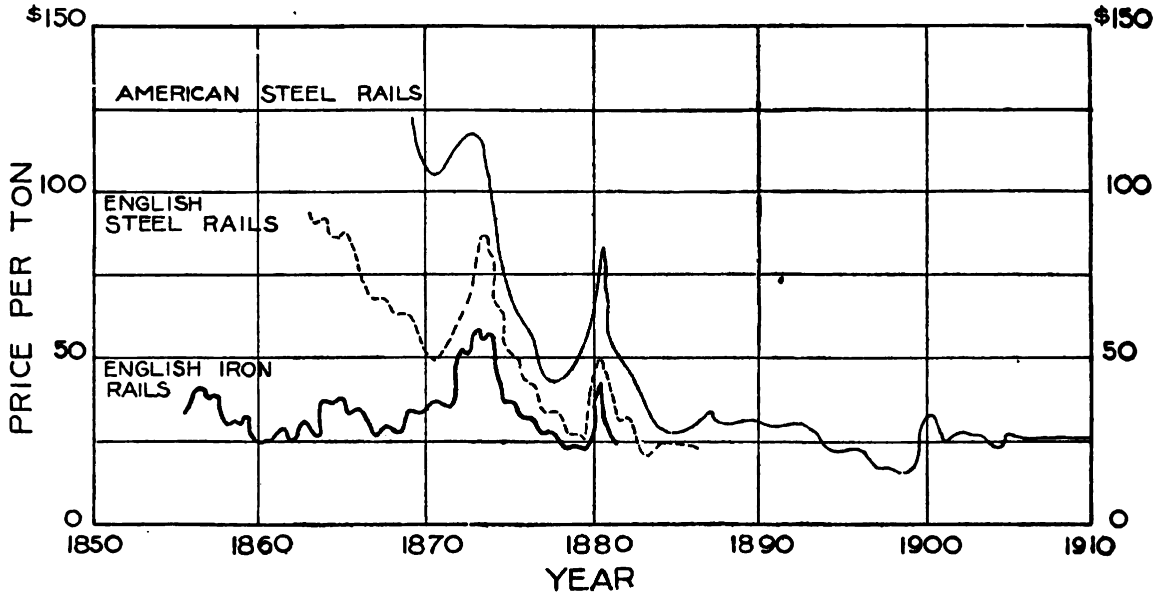


FIG. 220. — Prices of Iron and Bessemer Steel Rails, 1855 to 1910.

which, so far as could be ascertained, were free from streaks . . . It is believed to be metallurgically feasible to produce better steel than has at times been offered and accepted."

No doubt the failures which have their origin in defective metal are considerably augmented by the character of the stress in the rail. On account of the concentration of the load on a small area, the stress is not distributed, and consequently a metal of a great degree of uniformity is required.

With the large wheel loads now in use the injurious effect of inferior material in the rail is much more apparent than in other structures not subjected to such highly localized stresses. The situation calls for a refinement of manufacture not generally realized in practice, and is further complicated by the desire for high carbon to resist the head stresses, with the need for physical properties in the other parts of the rail which could best be obtained by the use of a much milder steel.

29. Chemical Composition

It was supposed that the chemical character of the steel in the earlier rails accounted for their excellent wear. Among the makers of these rails, Sir John Brown & Co., of Sheffield, England, sent to this country those which, from their excellent service, were considered by railroad engineers as the type of what rails should be. Accepting the chemical theory, rail makers expected that the analyses of these celebrated rails would present steel of exceptional uniformity and purity. The contrary was proved to be the case. Carbon varied from .24 to .70; silicon, .032 to .306; phosphorus, .077 to .156; sulphur, .050 to .181; manganese, .312 to 1.046. The following is the variation found in thirteen rails made by John Brown & Co., England, all of which had given good service:

	Per cent.		Per cent.
Carbon	0.24	to	0.70
Manganese	.312	to	1.046
Phosphorus	.077	to	.156
Sulphur	.050	to	.155
Silicon	.032	to	.306

Below is given the analysis of some of the earliest English rails, imported between 1860 and 1870. These rails, low in carbon and all other hardening constituents, have given from thirty to thirty-five years' service before wearing out, not breaking.

	Rails Used on Southern Railway.	Rails Used on P., C., C. & St. L. Railway.	
	Per cent.	Per cent.	Per cent.
Carbon	0.158	0.273	0.22
Manganese	.77	.28	.21
Phosphorus	.114	.05	.05
Sulphur	.067	.04	.031
Silicon	.490	.025	.035

Fig. 221 shows the performance of two rails of very similar chemical composition, which, however, possessed quite different wearing qualities.

* In 1881, Dr. C. B. Dudley, the chemist of the Pennsylvania Railroad, made an investigation to determine the relative relation between the chemical and physical characteristics of steel rails and their power to resist wear. Dr. Dudley found for the average of 32 slow-wearing rails the following composition:

	Per cent.
Carbon	0.334
Phosphorus	0.077
Silicon	0.060
Manganese	0.491

* The Wearing Capacity of Steel Rails in Relation to Their Chemical Composition and Physical Properties, C. B. Dudley, Trans. American Institute of Mining Engineers, Vol. IX (1880–81), p. 321.

and proposed a formula for the correct composition of steel rails, as follows:

		Per cent.
Carbon,	between .25 and .35; aim at	0.30
Phosphorus,	not above	0.10
Silicon,	not above	0.04
Manganese,	between .30 and .40; aim at	0.35

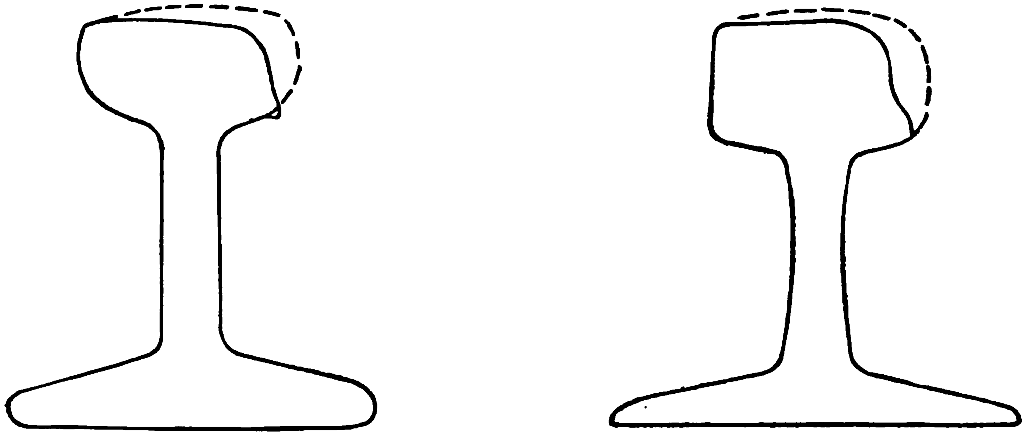


FIG. 221. — Comparative Wear of Rails of Similar Chemical Composition. (Trans. A. S. C. E. 1889.)

Chemical Composition	0.322 per cent.	Carbon	0.355 per cent.
	0.026 per cent.	Silicon	0.029 per cent.
	0.077 per cent.	Phosphorus	0.108 per cent.
	0.492 per cent.	Manganese	0.490 per cent.
Year Rolled	1871		1876
Time in Service	August, 1871 to July, 1879 7 years, 11 months.		August, 1876 to July, 1879 2 years, 11 months.
Location	On high side of 5° Curve Grade 39.6 ft. per mile.		On high side of 5° Curve Grade 39.6 ft. per mile.
Tonnage over Rail	40,061,230 tons.		21,504,824 tons.

Table LXXXIV gives the result of his experiments.

TABLE LXXXIV. — WEAR OF RAILS
(Dudley.)

Kind of Service.	Number of Rails.	Average Loss of Metal.	Number of Million Tons to Lose 8 Pounds.
Level tangents	16	.0384	208.4
Grade tangents	16	.0701	114.1
Level curves	16	.0706	113.3
Grade curves	16	.1277	62.7
Low side level curves	8	.0500	160.0
High side level curves	8	.0911	87.8
Low side grade curves	8	.0801	98.9
High side grade curves	8	.1754	45.7
Tangents	32	.0542	147.6
Curves	32	.0992	80.6
Levels	32	.0545	146.8
Grades	32	.0989	80.9
Low side curves	16	.0650	123.1
High side curves	16	.1332	60.1
All conditions	64	.0767	104.3
32 slower wearing	32	.0506	158.1
32 faster wearing	32	.1028	77.8

Wellington states that the result of this investigation, which showed, or seemed to show, that very hard rails did not wear so well as softer and tougher rails, was taken to indicate that softness in itself was a desirable quality in a rail; and the painstaking character of the investigation and high reputation of the road having given these conclusions wide dissemination, manufacturers for many years took them as a guide, and produced rails that were too soft.

Table LXXXV shows the gradual increase of the hardening constituents in the steel for rails since Dr. Dudley's investigation.

TABLE LXXXV.—COMPARISON OF THE CHEMISTRY OF EARLY AND RECENT RAILS

Name.	Date.	Weight of Rail.	Chemistry.										
			Carbon.			Manganese.		Silicon.		Sulphur.		Phosphorus.	
		Lbs. per yd.	Des'd.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
			Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
Dr. C. B. Dudley	1881		.30	.25	.35	.30	.40		.04				.10
Pennsylvania R.R.	1885			.30	.50								
Queen & Crescent	1892	75		.42	.47						.05*		.10*
Michigan Central R.R.	1896	80		.45	.55	.85	1.15	.10	.20		.07		.09
Norfolk & Western Ry	1899	85		.55	.63	.90	1.10	.10	.14		.04		.085
The Carnegie Steel Company	1899	50- 60		.35	.45	.70	1.00						
		60- 70		.38	.48	.70	1.00						
		70- 80		.40	.50	.75	1.05		.20				.10
		80- 90		.43	.53	.80	1.10						
		90-100		.45	.55	.80	1.10						
Pennsylvania R.R. (Bessemer)	1908		.50	.45	.55	.80	1.20	.05	.20				.10
Harriman Lines (Bessemer)	1909	90		.55	.65	.80	1.05		.20				.085

* Metal from which steel is made.

It has often been stated that the reason why the earlier rails seem to last so well was due to the elimination of the poorer quality of rails by the service in the track. This statement is not the complete explanation. The older rails were cold rolled by the light wheel loads until the surface was sufficiently hardened to bear the recent heavier loads without much increased abrasion. New rails of the same section and practically the same physical properties would, when subjected to heavier wheel loads, lose more of the metal by wear, before the surface was rolled as hard as the former sections, and their rate would be much faster.*

The light earlier sections could carry from 60 million to 75 million tons before they were rough and unsuitable for passenger traffic, and, when in a location where the tonnage was only 250,000 to 500,000 tons per month, would last in the track many years.

The six-inch 100-pound Dudley sections of 0.06 phosphorus and 0.65 carbon laid in 1895 on the New York Central and Hudson River Railroad, when taken up in 1907 had carried 375 million tons with a loss of about one-eighth of an inch in depth on the head of the rail.

* Paper by Dr. P. H. Dudley before the Railroad Commission of Indiana, February 20, 1912.

Carbon is the most important element, except iron, in steel. The mechanical properties of iron-carbon alloys are closely connected with the relative amounts of the two elements. The relation between the percentage of carbon in an alloy and the tenacity in tons per square inch is indicated* in the following table:

Per cent of carbon =	0.05	0.1	0.2	0.4	0.6	0.8	1.0	1.3
Tenacity, tons per sq. in. =	25.00	26.0	31.0	36.0	43.0	58.0	60.0	44.0

The results are shown graphically in Fig. 222.

Silicon in small proportions hardens the steel and stands intermediate between carbon and phosphorus in this respect. It is used to prevent unsound or honey-combed ingots, but when so used tends to render the steel unduly hard. Silicon as high as .2 per cent, in high-carbon steel of .5 and .6 per cent carbon, probably has no injurious effect.

Phosphorus hardens steel more rapidly than either carbon or silicon. It increases its rigidity but impairs its power to resist impact. Small proportions render the metal harder without materially affecting its tenacity, but makes the metal at the same time decidedly cold-short. An excess of phosphorus also renders the steel sensitive to high heat. Mr. Robert W. Hunt, in his experiments in trying to make high phosphorus steel in the Clapp-Griffith converter, found that it was necessary to be very careful not to over-heat the steel.

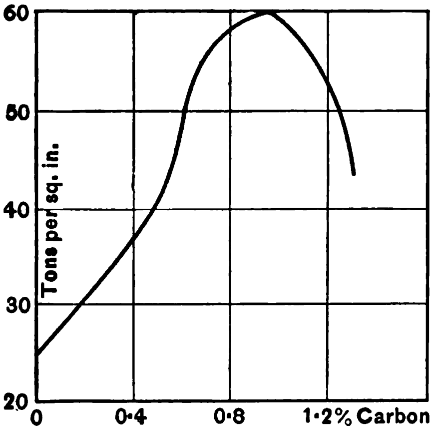


FIG. 222.—Tenacity of Iron-Carbon Alloys. (H. M. Howe.)

† Owing to the exhaustion of the available low-phosphorus ores, Bessemer rail steel is now of necessity a high-phosphorus and low-carbon alloy, the mean carbon being about 0.50‡ per cent, while the impurity of phosphorus is limited to 0.10 per cent.

Plain basic open-hearth rail steel is usually a low-phosphorus and medium unsaturated carbon alloy, as most of the phosphorus has been reduced by this

* H. M. Howe, Engineering and Mining Journal, p. 241, 1887. See also Steel by Harbord and Hall, London, 1911, pp. 347, 348, and a Study of the Elastic Properties of a Series of Iron-Carbon Alloys, Jones and Waggoner. Proceedings American Society for Testing Materials, Vol. XI, 1911, pp. 492–499.

† See Proceedings American Society for Testing Materials, Vol. XI, 1911, Dudley, Ductility in Rail Steel.

‡ The chemical composition refers, in this and the following example, to 100-pound rails.

process from its content in the ores and iron to 0.04 per cent or under. This permits, in this class of steel rails, carbon of 0.63 to 0.75 per cent.

Sulphur has little influence on the tensile strength or ductility. The real effects of sulphur, however, are seen during the rolling, a very small percentage causing a great red-shortness. Its presence in excess of .06 or a maximum of .08 per cent tends to cause cracks to develop during the rolling, which, while they close up and are almost imperceptible in the finished rail, nevertheless remain as flaws and may form starting points for rupture when the rail is subjected to any sudden stress. With sulphur, it is necessary to work the metal at a high heat to avoid its cracking during manipulation. The "red-short" term means that as the heat approaches the red color the tendency to crack becomes intensified, while the effect of phosphorus on heated metal is to make it hot short or short under high heat; in other words, it will work at a low temperature, but is sensitive to a high one.

Apparently the greater part of the sulphur unites with the manganese forming manganese sulphide, which is occluded by the metal as a foreign substance, preventing its welding and breaking up the continuity of its structure. The impurity of sulphur was limited formerly to 0.075 or 0.08 per cent. The manufacturers now charge for this limitation of sulphur five cents extra per hundred pounds, and it is, therefore, being omitted from some specifications, although in most cases it is required that its content be reported.

Manganese has a general tendency to increase the tensile strength and reduce the ductility; this influence varying with the amount of carbon present in the steel and becoming more marked in the case of high-carbon than low-carbon steels. It is possible to keep the manganese down, by the use of a low manganese spiegle, and with low-sulphur steel its presence in excess of .8 per cent, or its use to bring up the tensile strength in place of carbon, is dangerous on account of its very distinct hardening effect when above .6 per cent. In the commercial run of iron, where the sulphur varies, the practice is to allow the manganese to go as high as 1.1 per cent, and some authorities do not consider it dangerous unless above 1.0 per cent even with low sulphur. Manganese tends to neutralize the effect of sulphur and prevent the metal becoming red-short, and, to a limited degree, the cold-shortness produced by phosphorus.

The above elements are those generally considered in rail steel, and specifications rarely refer to the other elements which may be contained in the ore, and which either from design or accident are present in the finished product. The most important of these are arsenic and copper.

The effect of arsenic upon steel was quite fully investigated several years

ago by Harbord and Tucket.* The conclusions given by them may be summarized as follows:

Arsenic, in percentages not exceeding .17, does not appear to affect the bending properties at ordinary temperatures, but above this percentage cold-shortness begins to appear and rapidly increases. In amounts not exceeding .66 per cent the tensile strength is raised very considerably. It lowers the elastic limit and decreases the elongation and reduction of area in a marked degree.

Messrs. Ball and Wingham † have investigated the influence of copper on the tensile strength of iron and steel. An alloy containing:

	Per cent.
Copper	7.550
Carbon	2.720
Manganese	0.290
Silicon	0.036
Phosphorus	0.130
Sulphur	0.190

was bright, white in color, crystalline, and very hard, but did not offer any great resistance to impact. Varying quantities of the alloy were melted down with Bessemer steel, and test pieces 1 inch by $\frac{1}{4}$ inch by $\frac{3}{16}$ inch were annealed before being tested. The following table shows the results:

Number.	Copper.	Carbon.	Tensile Strength.
	Per cent.	Per cent.	Tons per sq. in.
1	0.847	0.102	18.3
2	2.124	0.217	36.6
3	3.630	0.380	47.6
4	7.171	0.712	56.0

From these experiments it is clear that copper increases the tensile strength of iron. ‡ The simultaneous presence of carbon tends to prevent the more intimate association of copper with iron. In test piece No. 1, the fractured surface was somewhat fibrous, while No. 2 and the others were highly crystalline. Even in the absence of carbon, copper makes iron extremely hard. Mr. F. Stubbs states that the presence of $\frac{1}{2}$ per cent of copper in steel gives to it the property of preventing the oxidation of the steel on being subjected to a burning heat.

Copper in steel rails in small quantity does not materially affect the mechanical properties, but in steels, in which high ductility is required, especially in those with high carbon, copper is objectionable. Steel with copper, say up to 1 per cent, appears to resist corrosion better than the same steel without

* On the Effect of Arsenic on Mild Steel, Journal Iron and Steel Inst., Vol. 1, 1888, p. 183.

† Iron and Steel Inst., No. 1, 1889.

‡ Steel and Iron for Advanced Students, Hiorns, London, 1903, p. 322.

copper. * Campbell states that 1 per cent may be present without injuring the steel, provided there be but little sulphur; but that if the sulphur be up to .08 or .10, the metal will be red-short, and that copper also reduces the welding power of the metal, especially if sulphur be present; but he adds: " In all cases the cold properties seem to be entirely unaffected." † Richards states that "copper causes red-shortness, but much less than sulphur. Five-tenths per cent may be allowed in rails and its effect is overcome by manganese."

‡ The influence of copper on steel was formerly greatly exaggerated. Whereas it was considered to be very harmful, it is now known, when present in small quantities, to have no serious influence on the physical properties of steel.

Mr. H. J. Force reports a case of an 80-pound rail made by the Lackawanna Steel Company in 1895, which had given very good service. An analysis showed about .40 per cent carbon and about .60 per cent copper.§

According to a statement in Professor Howe's " Metallurgy of Steel " ‖ an American firm of steel-rail makers habitually made Bessemer tee rails with .51 to .66 per cent copper and they were so slightly red-short that in spite of the thin flanges and low finishing temperature only from 1.25 to 2.5 per cent of them were so defective as to be classed as second quality.

Mr. R. W. Hunt states that in the early days of the steel industry excellent rails were produced from Cornwall irons. A large number of these rails contained .5 per cent of copper. The Pennsylvania Steel Company, as well as the Bethlehem and the Troy Works, used Cornwall iron containing low phosphorus and high copper as their basis for a long time.

Clamer ¶ has found that the addition of copper and nickel in combination seems to have the same effect upon the steel as if they were individually added, the copper in its effect really being about the same as so much added nickel. It is possible, therefore, to replace part of the nickel in nickel steel by copper, without materially altering its physical properties. Recently Messrs. Burgess and Aston, working quite independently of Clamer, have confirmed these results.

The attention of railroad engineers is being directed toward the development of alloy steel, or steel containing a percentage of various materials introduced to give it special mechanical qualities. In general, however, on account of the higher cost of production, these steels are confined to use in special locali-

* Metallurgy of Iron and Steel, A. Humboldt Sexton, Manchester, 1902, p. 247.

† Notes on Iron, Robert H. Richards, 1895.

‡ Metallurgy of Steel, Harbord, London, 1911, p. 375.

§ Proceedings American Society for Testing Materials, Vol. X, 1910, p. 279.

‖ Metallurgy of Steel, New York, 1891, p. 83.

¶ Proceedings American Society for Testing Materials, Vol. X, 1910, Clamer on Cupronickel Steel.

ties where the conditions are especially severe, as on sharp curves under heavy traffic or in tunnels where it is a troublesome matter to inspect or renew the rails.

The requirements of steel alloy may be summarized as follows:

(1) High resistance to shock;
(2) High elastic limit;
(3) Resistance to abrasion.

Some of the alloys best known are manganese, nickel, chromium, and titanium.

* The record of the chrome nickel on the Central Railroad of New Jersey, and of the plain nickel on the Pennsylvania Lines, Northwest System, is not very good. In a period of six months there were 112 failures per 10,000 tons laid of 85-pound A. S. C. E. section of nickel steel from the Carnegie Steel Company on Pennsylvania Lines, Northwest System, the chemical composition being:

	Per cent
Carbon	.44
Phosphorus	.09
Manganese	.80
Silicon	.10
Sulphur	.03
Nickel	3.42

The 90-pound A. S. C. E. section chrome nickel steel from the Bethlehem Steel Company on the Central Railroad of New Jersey for the same period showed failures of 41 per 10,000 tons laid, nearly all of which were broken rails.

The same committee reported for the year, ending October 31, 1910, that the record for 90-pound A. S. C. E. open-hearth rail with chromium and nickel on the Central Railroad of New Jersey has been very bad so far as failures are concerned, there having been 1,129 per 10,000 tons of rail laid, mostly breakages. This rail is 1909 manufacture. Small lots have also been tested on the Baltimore and Ohio and the Erie with a large number of failures. The amount of nickel is 2 per cent to $2\frac{1}{2}$ per cent, and the chromium 0.5 per cent to 0.9 per cent. In most cases these rails showed a very marked resistance to flange wear as compared with ordinary carbon steel rails.

It has been found desirable to lower the carbon when the other hardening elements are added. A rail with carbon 0.40, chrome 0.50, and nickel 1.25 is about equal to a 0.60 carbon ordinary rail.

Manganese steel with C 0.77, P 0.06, Mn 9.93, Si 0.25, and S 0.038 showed about one-third as much abrasion of the head as ordinary Carnegie Bessemer in a test, on the Norfolk and Western, lasting nineteen months.

* Proceedings Am. Ry. Eng. & M. of W. Assn., Vol. 11, Part 1, 1910, p. 315.

Chrome steel, which usually contains about 2 per cent of chromium and .80 to 2 per cent of carbon, owes its value to combining, when in the " hardened" or suddenly cooled state, intense hardness with a high elastic limit, so that it is neither deformed permanently nor cracked by extremely violent shocks.

* The tensile strength rises with increase in the percentage of chromium till with about 5 per cent it is about 74 tons unannealed, or 55 tons annealed, the elongation being 13 per cent in the latter and 8 per cent in the former case. The limit of elasticity was 40 tons in the first and 20 tons in the second case. As the quantity of chromium is increased the metal becomes harder, and with about 9 per cent can hardly be touched with the file. In the absence of carbon its hardening influence is not so marked. Forging makes the metal hard and brittle, but the latter property is removed by annealing, and it is rendered excessively hard by quenching. It has a high resistance to shock, and is therefore suitable for the manufacture of rails.

† On low-carbon steels not annealed, the addition of each 1 per cent of nickel up to 5 per cent causes, approximately, an increase of 5000 pounds per square inch in the elastic limit and 4000 pounds in the ultimate tensile strength. The influence of nickel on the elastic limit and ultimate strength increases with the percentage of carbon present, high-carbon nickel steels showing a greater gain than low-carbon nickel steels.‡

The addition of nickel to steel raises the proportion of elastic limit to ultimate strength and adds to the ductility of the steel. This effect of nickel in increasing the ratio of the elastic limit to tensile strength, without sacrifice to ductility, accounts for the increase in the working efficiency of nickel steel over carbon steel; in other words, its increased resistance to molecular fatigue.

The exhaustive series of experiments made by Wedding and Rudeloff show that the resistance to compression of nickel-iron alloys increases steadily with the per cent of nickel present, until 16 per cent of nickel is reached. Hadfield has also made a very complete series of experiments on the resistance of nickel steel to compression. He has found that a steel containing .27 per cent nickel shortened, under a compression of 100 tons (224,000 pounds) per

* Metallurgy of Iron and Steel, A. H. Sexton, Manchester, 1902, p. 517.

† Nickel Steel: Its Properties and Applications. Colby. Proceedings American Society for Testing Materials, Vol. III, 1903.

‡ The subject of nickel steel has received considerable attention, notably by D. H. Browne, Trans. American Institute of Mining Engineers, Vol. 29, 1899, p. 569, and A. L. Colby, "A Comparison of Certain Physical Properties of Nickel and Carbon Steel," Bethlehem Steel Company, 1903. See also Guillet, Journal, Iron and Steel Institute, Vol. 2, 1908, p. 177; Waterhouse, Proceedings Am. Soc. for Testing Materials, Vol. VI, 1906, pp. 249–258; Campbell and Allen, ibid, Vol. XI, 1911, pp. 428–438.

square inch, 49.90 per cent in a length of 1 inch; a steel with 3.82 per cent nickel shortened 41.38 per cent; with 5.81 per cent nickel, 37.76 per cent; and with 11.30 per cent nickel, only 1.05 per cent. He states that an ordinary mild carbon steel without nickel, under similar conditions, would be shortened 60 per cent to 65 per cent. He argues that the toughening action of nickel when added to steel is caused in a very intimate combination of the molecular structure, and that this advantage is further enchanced by the fact that the nickel does not show a disposition to segregate in steel like other elements; in other words, it appears to be more intimately combined.

Mr. Campbell, of the Pennsylvania Steel Company, made a series of tests to prove what he states to be the current impression among manufacturers of nickel steel, — that the presence of this element prevents segregation. His conclusion is, that there seems to be good ground for the assumption that nickel prevents the separation of the metalloids, but that it does not prevent it altogether, and he states that it is not probable that any other agent will ever be found competent for this task.

* Howe states that nickel steel, which usually contains from 3 to 3.50 per cent of nickel and about .25 per cent of carbon, combines very great tensile strength and hardness, and a very high limit of elasticity, with great ductility.

The combination of ductility, which lessens the tendency to break when overstrained or distorted, with a very high limit of elasticity, gives it great value for shafting, the merit of which is measured by its endurance of the repeated stresses to which its rotation exposes it whenever its alignment is not mathematically straight. The alignment of marine shafting, changing with every passing wave, is an extreme example. In a direct comparative test the presence of 3.25 per cent of nickel increased nearly sixfold the number of rotations which a steel shaft would endure before breaking.

As has been seen, nickel steel has been used tentatively for railroad rails; but while it has the stiffness and resistance to wear which they require, too many rails have broken in use. We may hope that this treacherousness will be prevented. It is quite possible that a change in the percentage of nickel may give an entirely different record. The Mayari ore used by the Maryland Steel Company contains a natural percentage of chromium and nickel, and the results with rail made from this ore seem, so far, to be pretty good.

Figs. 223 and 224 give the tensile strength and the ductility of many specimens of nickel steel from various sources, chiefly, however, from M. Dumas'

* Iron, Steel, and Other Alloys, Howe, 1903, pp. 316–324. Contains report of M. Dumas' work.

important monograph.* The curves here given are taken from his work (pages 18 and 19). A rough resemblance to the manganese steel curves (Figs. 225 and 226) may be noticed. The great increase of ductility in case of manganese steel in the 13 per cent manganese region is reflected in case of nickel steel by a like and very abrupt rise at about 25 per cent of nickel.

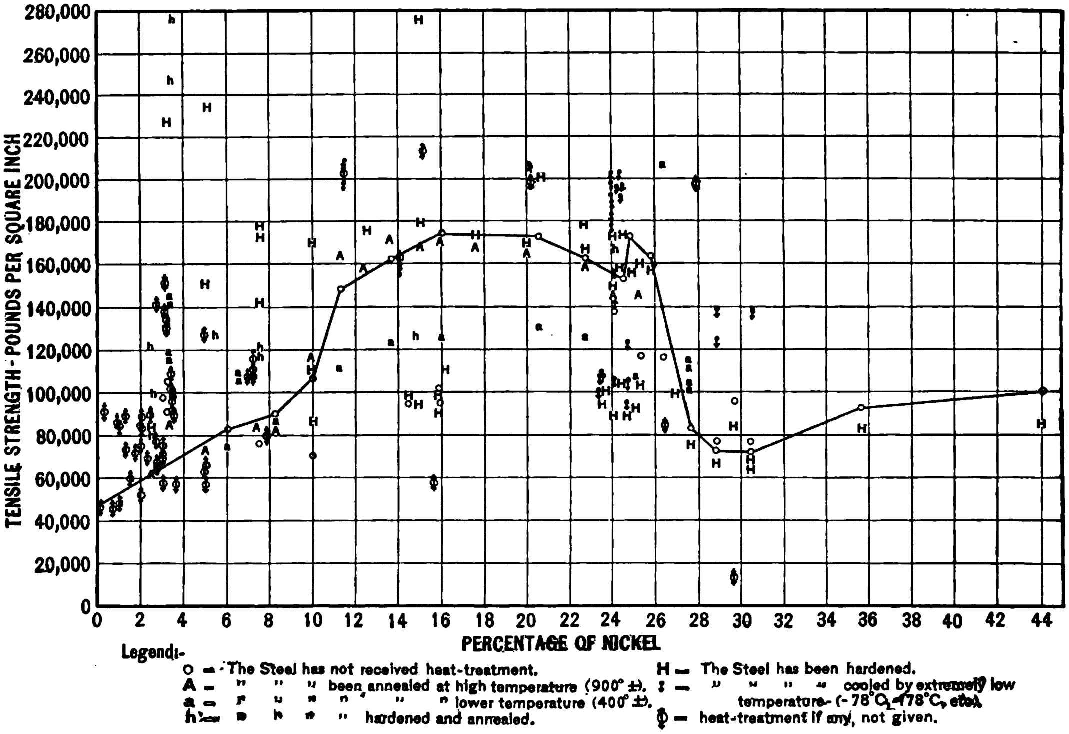


FIG. 223. — Influence of the Proportion of Nickel and Varying Heat-Treatment upon the Tensile Strength of Nickel Steel. (Dumas.)

As actually made, manganese steel contains about 12 per cent of manganese and 1.50 per cent of carbon. Although the presence of 1.50 per cent of manganese makes steel brittle, and although a further addition at first increases this brittleness, so that steel containing between 4 and 5.5 per cent can be pulverized under the hammer, yet a still further increase gives very great ductility, accompanied by great hardness, — a combination of properties which, so far as known, was not possessed by any other known substance when this remarkable alloy, known as Hadfield's manganese steel, was discovered.

Its ductility, to which it owes much of its value, is profoundly affected by the rate of cooling. Sudden cooling makes the metal extremely ductile, and slow cooling makes it brittle; its behavior in this respect is thus the opposite of

* "Recherches sur les Aciers au Nickel à Hautes Teneurs," M. L. Dumas, Paris, 1902.

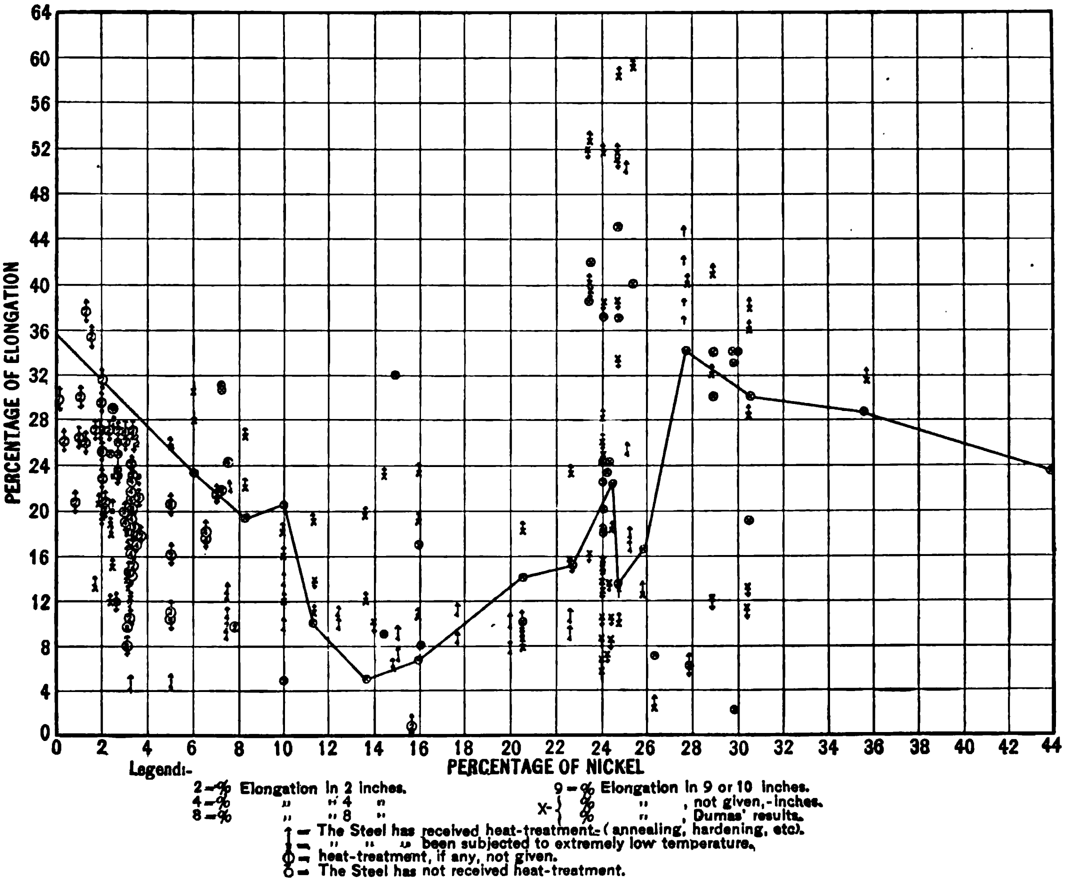


FIG. 224. — Influence of the Proportion of Nickel and Varying Heat-Treatment upon the Ductility of Nickel Steel. (Dumas.)

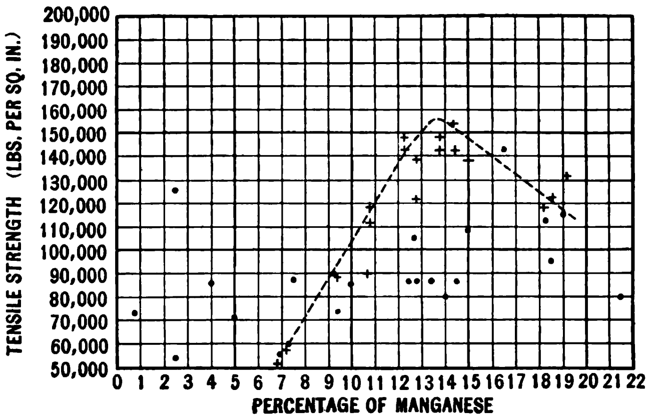


FIG. 225. — Influence of the Proportion of Manganese on the Tensile Strength of Manganese Steel. (Howe.)

Legend:

• = Slowly Cooled Manganese Steel.

+ = Water-toughened or Suddenly Cooled Manganese Steel.

that of carbon steel. Its great hardness, however, is not materially affected by the rate of cooling.

The fact that when cold it is unalterably hard has, however, limited its use, because of the great difficulty of cutting it to shape, which has in general to be done with emery wheels instead of the usual iron-cutting tools. Another defect is its relatively low elastic limit.

Fig. 225 shows the remarkable increase of tensile strength which occurs when the manganese rises from 7 to 13 per cent, and the decline of tensile strength as the manganese increases still further. By the contrast between the position of the crosses and the black dots it shows also the remarkable effect of sudden cooling.

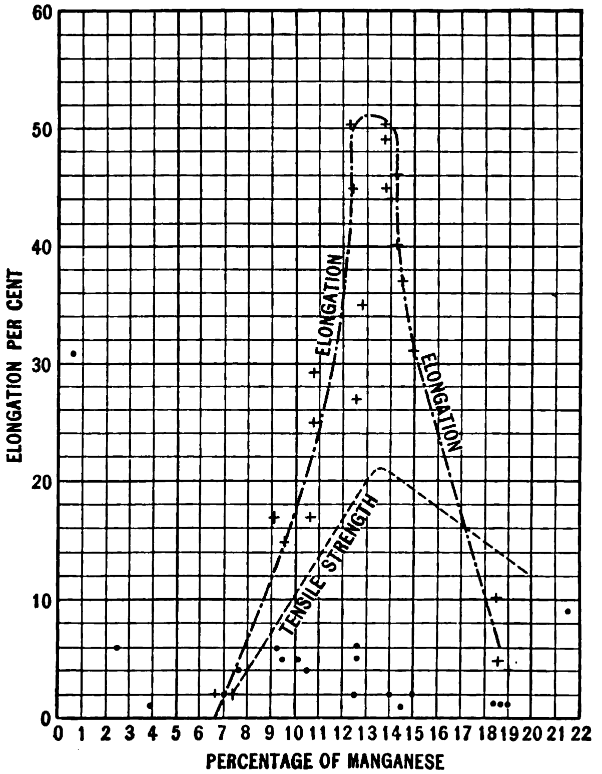


Fig. 226. — Influence of the Proportion of Manganese on the Ductility of Manganese Steel. (Howe.)

Legend:
- • = Slowly Cooled Manganese Steel.
- + = Water-toughened or Suddenly Cooled Manganese Steel.

Fig. 226 shows the corresponding changes in ductility. To show that the maxima for tensile strength and ductility coincide, the tensile-strength curve sketched by eye in Fig. 225 is reproduced in Fig. 226.

In Fig. 227 is shown the degree to which manganese steel combines tensile strength with ductility, and in Fig. 228 the degree to which it combines ductility with elasticity. These combinations are often taken as a rough measure of the general degree of excellence of a metal for engineering purposes. For comparison the corresponding properties of carbon steel are shown by small black dots, which fall in a pretty well-defined band, much below the manganese-steel crosses.

These comparisons may, however, give a false idea of the ductility of manganese steel. If two metals elongate in a like manner, the extent of their elongation may be a fair comparative measure of their ductility; not necessarily so, however, when their mode of elongating is unlike in kind. A bar of carbon steel

habitually yields by "necking" when pulled in two, contracting greatly just about the place where rupture occurs, while a bar of manganese steel or of brass elongates far more uniformly over its whole length.

The use of manganese frogs in severe service on steam roads and for rails on curves of 75 feet radius or less for permanent street railway work has been found preferable to ordinary carbon open-hearth or Bessemer material.

Titanium steel, while not strictly an alloy steel, may be conveniently treated under this head. This metal, like vanadium, aluminum or silicon, produces a sounder ingot, and under the usual practice the titanium goes into the slag and ordinarily there is no intention of producing titanium alloy steel.

A progress report of the Baltimore and Ohio shows that the titanium rail with .70 carbon on Kessler's curve is only wearing one-third as fast as the Bessemer steel with .50 carbon, with which it is compared. The results of six months' service on a New York Central crossover carrying a heavy tonnage show that the flange wear of titanium rails was very much reduced as compared with that of ordinary Bessemer rails.*

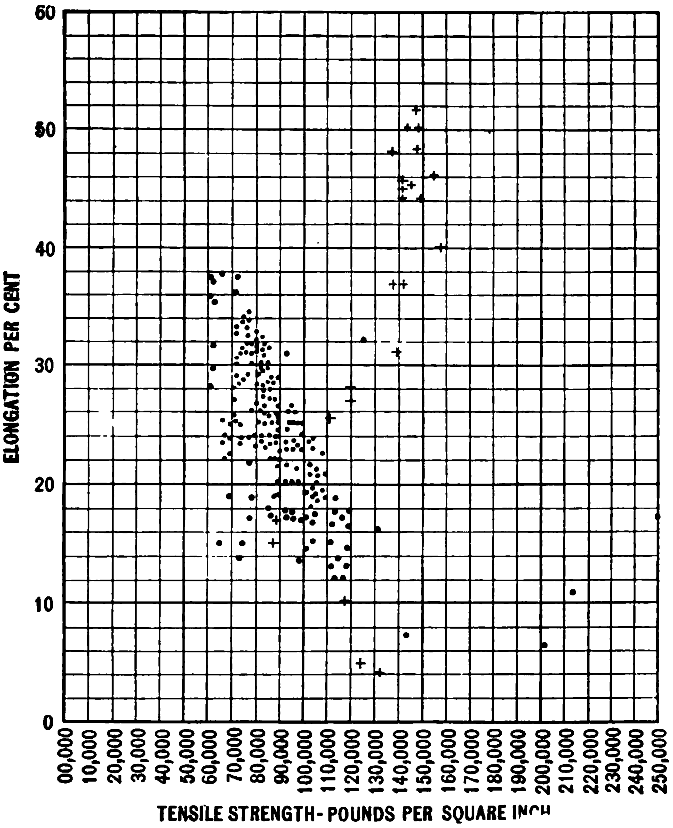


FIG. 227. — Tensile Strength and Ductility of Carbon Steel and of Manganese Steel. (Howe.)

Legend:
· = Carbon Steel.
+ = Water-toughened or Suddenly Cooled Manganese Steel.

† The effect of titanium on steel as understood to-day is to give the metal greater density and strength. Recent tests on titanium rail steel made by

* Iron Age, March 25, April 29, and August 5, 1909.

† The Use of Titanium Rail on the Baltimore & Ohio Railroad. A. W. Thompson. Proceedings Am. Ry. Eng. & M. of W. Assn., Vol. 11, Part 1, 1910, and Railroad Age Gazette, November 12, 1909.

Dr. Waterhouse show the elastic limit to be raised about 6000 pounds above the same steel to which the titanium alloy had not been added. In the 150 rails examined the titanium steel from different parts of the ingot showed a remarkable degree of uniformity.*

The first experiments with titanium alloy in rail manufacture were made by the Maryland Steel Company in November, 1907, and this was followed in 1908 by the Duquesne Works of the Carnegie Steel Company, the Cambria Steel Company, and the Lackawanna Steel Company. During the year 1909 the process passed the experimental stage and has since been used in a large number of rails and may be regarded as firmly fixed on a commercial basis.

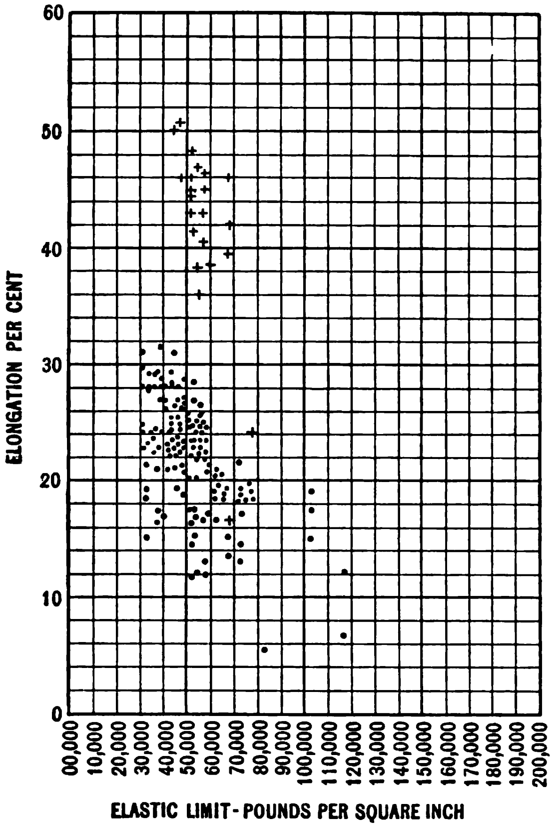


FIG. 228. — Elasticity and Ductility of Carbon Steel and of Manganese Steel. (Howe.)

Legend:
• = Carbon Steel.
+ = Water-toughened or Suddenly Cooled Manganese Steel.

During the month of June, 1908, 19 rails were rolled by the Maryland Steel Company, of the usual composition, to which was added 1.5 per cent titanium alloy. This alloy was claimed to increase the elastic limit, ultimate strength, and remove a large percentage of the slag; also to make the rail less brittle and avoid extreme segregation and blowholes, leaving the metal homogeneous, tough, and fine-grained. The use of the alloy resulted in a rail with a composition high in carbon and phosphorus, which even then successfully passed the physical test.

The analysis made by the Maryland Steel Company of this rail shows the following:

C.	Mn.	P.	S.	Si.	N.	O.
0.701	0.92	0.086	0.048	0.079	0.004	Nil

* See also C. V. Slocum, Mechanical Engineer, Vol. XXIII, 1909, pp. 336–337.

The addition of ferrotitanium to the ladle has an important influence on the mechanical structure of the steel by acting as a flux or scavenger, and the cleansing effect results in increased solidity and purity of the metal.

Ferrotitanium contains 10 to 15 per cent of titanium, 5 to 10 per cent of carbon, and of other impurities less than 5 per cent; the balance is pure iron which has been electrically refined. In Bessemer steel rail manufacture it is the practice to add from $\frac{3}{10}$ to 1 per cent crushed ferrotitanium in the ladle as the steel is poured from the converter, and then hold the heat in the ladle about three minutes before pouring the ingot. Sulphur and phosphorus do not appear to be reduced; but in combining with oxygen and nitrogen, forming oxides and nitrides, titanium has an important action in removing these impurities, forming a stable combination of them, which passes into the slag.

The New York Central Lines, prior to 1911, obtained rails from the Lackawanna Steel Company with $\frac{3}{10}$ of 1.0 per cent of ferrotitanium alloy added to the ladle. The addition to the cost for plain Bessemer was 25 cents per ton for holding the metal in the ladle three minutes after the ferrotitanium was added and $1.05 per ton for the alloy, or a total of $1.30 per ton. In 1911 $\frac{1}{10}$ of 1.0 per cent of metallic titanium was added to the metal and the price subsequently reduced, owing to a reduction in the cost of ferrotitanium. It is claimed that this small proportion of ferrotitanium is sufficient to remove the bulk of blowholes and segregation usually found in Bessemer ingots and produce a clean, solid, good-wearing rail.

The following table * gives the production of alloy rails in the years 1909 and 1910. It appears that greater effort has been made to improve the Bessemer rail by the use of alloys than the open-hearth rail.

	1909	1910
	Tons.	Tons.
Ferrotitanium rails	35,945	195,940
Manganese rails	1,028	390
Nickel chrome rails	12,287	......
Nickel and electric rails	1,245	......
Electric rails	......	4,210
Nickel, chrome, and vanadium rails	......	81
Total	50,505	200,621
Bessemer steel	37,809	174,822
Open-hearth steel	12,696	25,799

Table LXXXVI gives the specification of chemical composition adopted as recommended practice by the American Railway Engineering Association March, 1912, for carbon steel rails. Table LXXXVII presents the chemical specification adopted January 1, 1909, by the Association of American Steel

* Railway Age Gazette, March 16, 1910 (daily edition), and the Iron Age, February 23, 1911, p. 461.

Manufacturers for standard Bessemer and open-hearth steel rails for A. S. C. E. sections.

TABLE LXXXVI

CHEMICAL COMPOSITION OF RAILS—American Railway Engineering Association

The chemical composition of the steel shall be within the following limits:

BESSEMER PROCESS

	70 lbs. and over, but under 85 lbs.	85–100 lbs. inclusive
	Per cent	Per cent
Carbon	0.40 to 0.50	0.45 to 0.55
Manganese	0.80 to 1.10	0.80 to 1.10
Silicon, not to exceed	0.20	0.20
Phosphorus, not to exceed	0.10	0.10

(When lower phosphorus can be secured, a proper proportionate increase in carbon should be made.)

OPEN-HEARTH PROCESS

	70 lbs. and over, but under 85 lbs.	85–100 lbs. inclusive
	Per cent	Per cent
Carbon	0.53 to 0.66	0.63 to 0.76
Manganese	0.60 to 0.90	0.60 to 0.90
Silicon, not to exceed	0.20	0.20
Phosphorus, not to exceed	0.04	0.04

(When higher phosphorus is used, a proper proportionate reduction in carbon should be made.)

TABLE LXXXVII.

CHEMICAL COMPOSITION OF RAILS.—Association of American Steel Manufacturers.

BESSEMER STEEL RAILS

	81 to 90 Pounds.	91 to 100 Pounds.
	Per cent.	Per cent.
Carbon	0.43 to 0.53	0.45 to 0.55
Phosphorus, not over	0.10	0.10
Silicon, not over	0.20	0.20
Manganese	0.80 to 1.10	0.84 to 1.14

OPEN-HEARTH STEEL RAILS

	81 to 90 Pounds.	91 to 100 Pounds.
	Per cent.	Per cent.
Carbon	0.59 to 0.72	0.62 to 0.75
Phosphorus, not over	0.04	0.04
Silicon, not over	0.20	0.20
Manganese	0.60 to 0.90	0.60 to 0.90

Table LXXXVIII gives the Pennsylvania specifications revised January 10, 1912, for 85-pound and 100-pound carbon steel rails.

TABLE LXXXVIII

CHEMICAL COMPOSITION OF RAILS.—Pennsylvania Railroad System.

BESSEMER STEEL RAILS

	Lower Limit.	Desired Composition.	Upper Limit.
	Per cent.	Per cent.	Per cent.
Carbon	0.45	0.50	0.55
Manganese	0.80	1.00	1.20
Silicon	0.05	0.12	0.20
Phosphorus	....	....	0.10

OPEN-HEARTH STEEL RAILS

	Classification A.			Classification B.		
	Lower Limit.	Desired Composition.	Upper Limit.	Lower Limit.	Desired Composition.	Upper Limit.
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
Carbon	0.70	0.75	0.83	0.62	0.70	0.75
Manganese	....	....	0.80	....	....	0.80
Silicon	0.05	0.12	0.20	0.05	0.12	0.20
Phosphorus	....	....	0.03	....	....	0.04

BIBLIOGRAPHY

General

LUTY, B. E. V. — Mathematical relations between increases in cost and increases in durability in steel rails. 1500 w. 1911. (In Railway Age Gazette, Vol. 51, p. 1223.)

DUDLEY, P. H. — Ductility in rail steel. 1800 w. 1911. (In Railway Age Gazette, Vol. 51, p. 289.) Paper before the American Society for Testing Materials.

Considers varying composition of rail steel and its influence on the wear.

SANDBERG, CHRISTER P. — Chemical composition of steel rails and latest developments. 4000 w. 1908. (In Bulletin of the International Railway Congress, Vol. 22, Part 1, p. 13.)

The same. (In Engineering, Vol. 83, p. 827.)

Discusses effect of different elements on quality and wear of metal.

Manganese Steel

Rolled manganese steel rail. 1200 w. Ill. 1908. (In Railroad Age Gazette, Vol. 45, p. 1536.)

Gives results of tests and shows comparative life of rails.

Rolled manganese steel rails. 1600 w. Ill. 1909. (In Iron Age, Vol. 83, Part 2, p. 1261.)

Discusses wear of Manard rail of the Pennsylvania Steel Company.

STEWARD, H. M. — Life of manganese steel rail on curves from service tests made on the elevated division of the Boston Elevated Railway Company. 1500 w. 1908. (In Proceedings of the American Street and Interurban Railway Engineering Association, Vol. 6, p. 333.)

The same. (In Electric Railway Journal, Vol. 32, p. 1196.)

Titanium Steel

DUDLEY, P. H. — Use of ferro-titanium in Bessemer rails. 3000 w. Ill. 1910. (In Journal of Industrial and Engineering Chemistry, Vol. 2, p. 299.)

Gives ductility tests of ferro-titanium rails showing them to average several per cent higher than ordinary Bessemer rails in ductility. Believes that range of ductility can be prescribed by proper study of chemical composition.

MALTITZ, ED. VON. — Der einfluss des titans auf stahl, besonders auf schienenstahl. 6000 w. Ill. 1909. (In Stahl und Eisen, Vol. 29, Part 2, p. 1593.)

The same, condensed. 1200 w. (In Iron Age, Vol. 84, Part 2, p. 1790.)

Gives results of experiments on effect of additions of titanium to Bessemer rail steel.

SLOCUM, CHARLES V. — Titanium alloy in rails and car wheels. 6000 w. Ill. 1909. (In Proceedings of the Railway Club of Pittsburg, Vol. 8, p. 176.)

Emphasizes the increased wear and soundness of titanium rails.

SLOCUM, CHARLES V. — Use of titanium in steel for rails, car wheels, etc. 2000 w. Ill. 1909. (In Electrochemical and Metallurgical Industry, Vol. 7, p. 128.)

Shows the increased durability and strength of titanium steel and its products.

SPRINGER, J. F. — Titanium steel. 2000 w. Ill. 1911. (In Cassier's magazine, Vol. 40, p. 483).

Considers especially its properties and importance as rail steel.

THOMPSON, A. W. — Use of titanium rail on the Baltimore and Ohio Railroad. 2500 w. 1909. (In Canadian Engineer, Vol. 17, p. 238.)

Gives properties and tests.

WATERHOUSE, G. B. — Influence of titanium on segregation in Bessemer rail steel. 3000 w. Ill. 1910. (In Proceedings of the American Society for Testing Materials, Vol. X, p. 201.)

Results indicate that presence of titanium in rail steel lessens segregation and promotes uniformity.

30. EXTRACTION OF THE IRON FROM ITS ORE

Before the process of reduction or "smelting" is attempted at the blast furnace the ore is usually subjected to some preliminary treatment.*

The preparatory processes are:

(a) "Grading" the ore;

(b) Calcination or roasting;

(c) Mixing to make up the desired proportions of ore charge.

The grading of the ore is not necessary at the furnace when it has already been properly done at the mine. When the sorting at the mines has not been carefully done, or when a greater number of grades than usual are required, sorting is also practiced at the furnace, and the ore is then distributed to the several bins of the stock house, which building is erected as near the furnace stack as possible.

† The purpose of roasting is to remove sulphur, carbonic acid, and water and to increase the porosity of the ore. It is accomplished in two ways, — by roasting the ore in a heap, or in a kiln using wood, coal, or gas for fuel. Fig. 229 shows the ore roasters used at the Norway furnace, Bechtelsville, Pa., in 1883.‡

Lake Superior ores require no roasting, and for this reason very little roasting of the ore is necessary at the present time. The iron ores in the vicinity of Johnstown, which were formerly used by the Cambria Steel Works, contain high sulphur and phosphorus content. The iron content in the ore was but 30 per cent, necessitating roasting before charging into the furnace. These works now use Lake Superior ores having an iron content of from 50 to 65 per cent, and the process of roasting is not necessary.

Making up the furnace charge is an operation which demands both a knowledge of the chemistry of the blast furnace and of ores. The proportions of the charge are determined by the character of the ore, the fuel, and the flux, by the size and method of working the furnace, and by the character of product required.

* Iron and Steel, Materials of Engineering, Thurston, Part 2, 1909, p. 91.

† Notes on Iron, Richards.

‡ Roasting Iron-Ores, by John Birkinbine. Trans. American Institute of Mining Engineers, Vol. XII (1883–4), pp. 361–379.

The location of the plant is usually chosen according to the cost of assembling these materials and getting the product to the market. Other things being equal, that furnace will be most economically located which is placed near the mines. Where the ores and fuel are widely separated, location is often determined by the facilities for marketing the iron, and the furnace is so placed that the total of all the costs of transportation and of working shall be a minimum.

PLAN

VERTICAL SECTION

ELEVATION

FIG. 229 — Ore Roasters, Norway Furnace, 1883. (Am. Inst. of Mining Engineers.)

If the quantities transported are O', O'', O''' respectively, and the cost of carriage is c dollars per ton, the distance for each being S', S'', S''', the total cost (Thurston),

$$K = cO'S' + cO''S'' + cO'''S''',$$

should, other things being equal, be made a minimum.

The notable present tendency in the iron industry is the lower average iron content in the ores used.* This tendency will undoubtedly continue in the future as the more easily accessible portions of the richer deposits are worked out. As a corollary to this is the observed tendency toward a decentralization of the

* Iron Ores of the United States. Report of the National Conservation Commission, Vol. III, p. 483, February, 1909. Government Printing Office, Washington.

Fig. 230. — Open Pit Mine on Mesaba Range, Mountain Iron Mine, near Hibbing, Minnesota, Steam Shovel Proposition.

Fig. 231. — View of the West Cut, looking North, Biwabik Mine.
(Am. Inst. of Mining Engrs.)

FIG. 232.—Steel Ore Dock at Two Harbors, Minn. Duluth and Iron Range Railroad.

iron industry, and with a decrease in the iron content of the ore used, involving a corresponding increase in cost of transportation per unit of iron, there will be an increase in the proportion of fuel which goes to the region producing the ore.

Sir I. Lowthian Bell in 1884 stated * that while "Wages (in America) are high . . . the geographical position of the ore and coal and of the markets themselves constitute obstacles of a far more insurmountable description. The distances over which ore is conveyed are sometimes very great; as an example,

FIG. 233. — Steamer "Augustus B. Wolvin," 560 ft. in length, capacity about 12,000 tons.

the produce of the Lake Superior mines is carried to Pittsburg, involving carriage of 790 miles. The cost of transport on the minerals consumed for each ton of pig iron I have calculated † to average 10*s*., 9*d*., at the eight chief seats of the iron trade in Great Britain; whereas, in the United States the mean charge at fourteen of the large centers is 25 *s*., 8 *d*." The introduction of improved methods for handling the ore in transport and the deepening of the waterways of the Great Lakes ‡ has in a measure overcome the adverse conditions mentioned above.

* Manufacture of Iron and Steel, Bell, London, 1884, p. 473.

† Report to Her Majesty's Government on Iron Manufacture of the United States compared with that of Great Britain.

‡ William Chandler, History of St. Mary's Falls Ship Canal, 1877. The Great Lakes and Our Commercial Supremacy, John Foord, North Am. Review, Vol. 167, p. 155. Saint Mary's Falls Canal Semicentennial, History of the Canal, John H. Goff, 1907.

General View of the Dock.

Side View of the Dock with Ore Cars on the Structure.

FIG. 234.—Great Northern Railway Ore Dock at Allouez Bay, Superior, Wis. (From Science Conspectus.)

Figs. 230 to 234 illustrate some of the features of the Lake Superior ore industry. Figs. 230 and 231 show the method of mining the ore by steam shovels employed in northern Minnesota. The shovels are large, with about 5-ton dippers. The amount of stripping required at these mines is often heavy, amounting in some cases to as much as 100 feet and costing from $0.25 to $0.40 per cubic yard of material removed from on top of the bed of ore. It is generally considered profitable to strip up to a maximum depth which does not exceed the thickness of the layer of ore uncovered.

Figs. 232, 233, and 234 show the ore docks and the type of vessels used in transporting the ore. * Down to late in the fifties the ore product of Lake Superior was handled over a mule-tram road to Marquette, and as late as 1870 a 700-ton ship was an enormous craft, the loading of which required two days and the unloading being seldom accomplished in that time.

In 1871 the largest ore barge carried 1050 tons, now the cargoes reach 14,000 tons. 165,000 tons of ore has been loaded into sixteen steamships in one day at the docks of the Duluth, Missabe and Northern Railway. The loading of the steamer " H. E. Corey " of 10,000 tons capacity at the Duluth and Iron Range Steel Ore Dock, at Two Harbors, Minn., was accomplished in 39 minutes.†

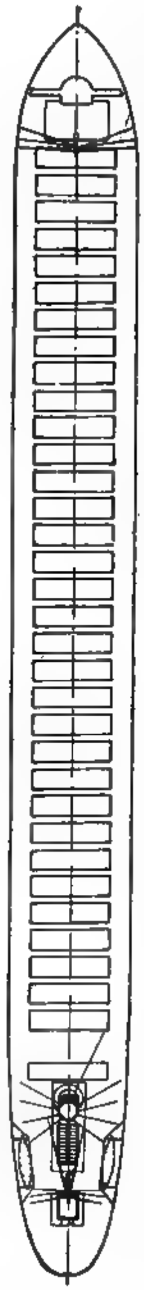


FIG. 235. — Transverse Section, In-board Profile and Plan, showing the one great Hopper Hold, 409 feet long, with 33 hatches. The "Wolvin;" a Typical Lake Steamer for the Transportation of Ore. Capacity 11,536 tons. (Scientific American.)

* The Development of Lake Superior Iron Ores. Bacon. Trans. American Institute of Mining Engineers, Vol. XXVII (1897), p. 341.

† Scientific American, December 11, 1909.

The construction of a special type of ship of large tonnage for ore trade, coupled with the invention of unloading machinery of great capacity at the terminal ports, has brought the cost of transportation down to a very low figure. Thus, a ton of ore is now hauled one hundred miles by rail from the most distant mines in the Lake Superior range to a Lake Superior port, is loaded into cars or into the stock pile at a Lake Erie port at a cost of less than $1.80 per ton.

FIG. 236. — Ten-ton Bucket of Unloader in Hold of the "Wolvin." (Scientific American.)

Fig. 235 presents an inboard profile and cross section of the "Wolvin," a representative of the type of present ore steamers. This vessel is 560 feet in length, 56 feet beam and 32 feet deep. The largest single cargo of ore carried by the "Wolvin" was 11,536 tons, a feat which she performed in 1904.

FIG. 237. — General View of Ore Unloader with Steamer at the Dock. (Railroad Age Gazette.)

The "E. H. Gary" in 1905 carried a single cargo of 12,368 tons. In 1906 the "J. P. Morgan" carried a single cargo of 13,272 tons of ore and in 1907 she carried 13,800 tons.

Fig. 238. — Brown Hoist Unloader Unloading Cargo of Ore; Grab Bucket lowered into Boat.
(Railroad Age Gazette.)

Fig. 236 shows the bucket of the Hulett ore unloader. Four of these machines located at the docks at Conneaut, Ohio, are credited with having taken out of the "Wolvin" 7257 gross tons of ore in four hours and six minutes.* The Hulett unloaders at Gary are showing an average rate of 300 tons per hour

FIG. 239. — Blast Furnace with Stoves and Buildings. (Thurston.)

for each machine. On July 10, 1912, the "Morgan" discharged 10,091 tons of ore in three hours and ten minutes at Conneaut. This was apparently the fastest time ever made in unloading, but on July 24, 1912, it was surpassed when the "Wm. P. Palmer" was relieved of 11,044 tons in three hours and seventeen minutes, or at the rate of 56 tons per minute.

* Saint Mary's Falls Canal Semicentennial, Commerce of the Great Lakes, Ralph D. Williams, 1907, p. 201.

Fig. 240.—Ground Plan, Showing the General Arrangement of Blast Furnace No. 4, Built at the Hazelton Plant of the Republic Iron and Steel Co. (The Iron Trade Review.)

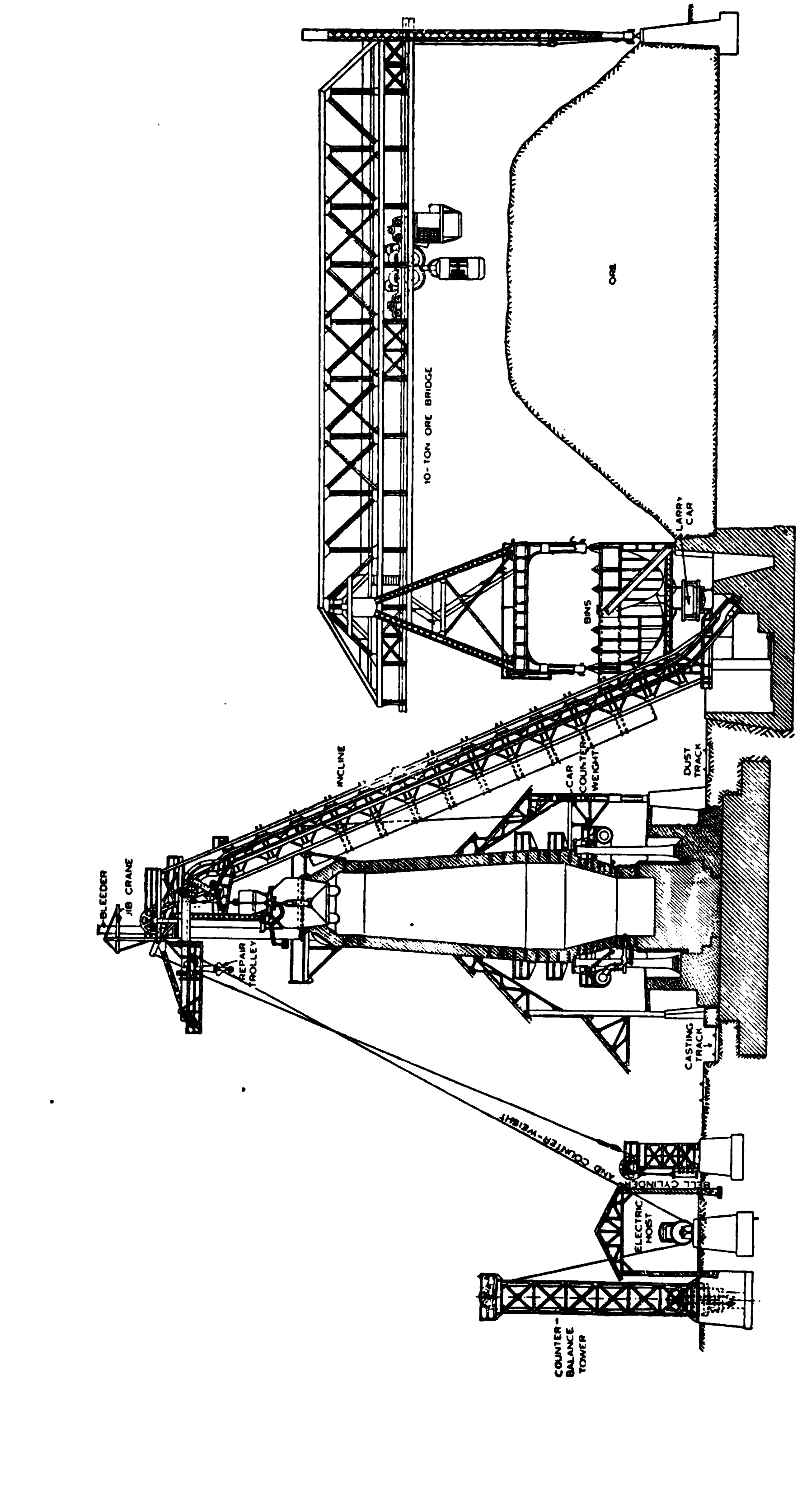


FIG. 241.—Sectional View of Hazelton Blast Furnace No 4. (The Iron Trade Review.)

* The coal and ore docks of the Baltimore and Ohio Railroad at Lorain, Ohio, are among the largest on the Great Lakes. The machinery for unloading the steamers is the latest design of Brown hoist unloader, driven by electricity and equipped with three grab buckets having a total capacity of 1000 tons of ore an hour. Figs. 237 and 238 illustrate a steamer being unloaded at the dock.

The large grab buckets employed scoop up from seven to ten tons of ore each time they are lowered into the hold of the vessel, after which they are hoisted and carried in over the dock on a movable girder, or ram, carried in a heavily braced portal frame, which is itself movable lengthwise of the dock.

The buckets may either be dumped into a 75-ton weighing hopper, from which the ore is discharged directly into cars on any one of the four tracks spanned by the unloader, or dropped into the trough space, which has a capacity of 100,000 tons, and is separated by a concrete wall from the tracks. Once deposited in the trough, the ore may either remain in temporary storage, or be conveyed to the larger storage space covered by the ore bridge.

The combination of fast unloading plants on the dock front with buckets moving at high speed over a short travel, with a storage bridge of long span, carrying a larger bucket over the storage space, is found on all modern lake docks.

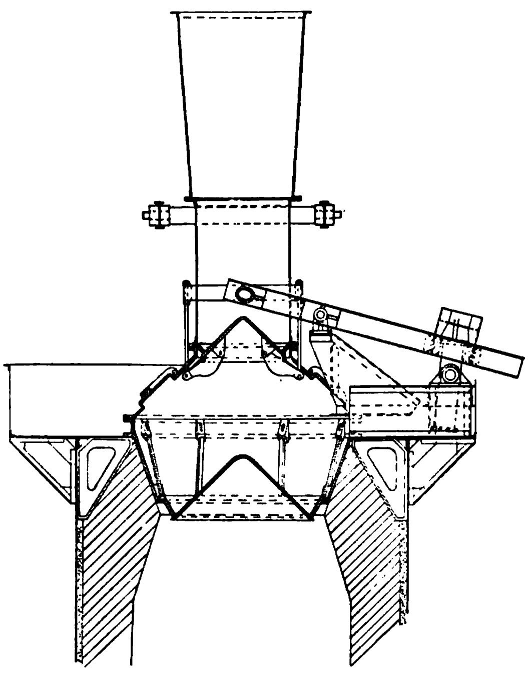


FIG. 242. — Top Rigging of Blast Furnace.

The blast furnace is shown by Figs. 239, 240, and 241. It is a brick structure, usually circular in section and built in two parts; the upper part resting on columns, while the lower portion rests directly on the foundation. The upper portion is sheathed with boiler plates. Fig. 242 shows the top rigging of a modern blast furnace. The charge is automatically elevated and dumped into the hopper.

In the United States furnaces are worked up to 100 feet high. The best modern practice is, however, about 90 feet high, with a product of 400 to 500

* Railway Age Gazette, July 28, 1911, p. 178.

FIG. 243. — The 450-ton Furnaces, Hot Stoves, and Gas-cleaning Plant in Course of Erection at Gary.
(Scientific American.)

tons per day. The following dimensions of the Gary furnaces are typical of the best practice. The blast furnaces (Fig. 243) are 88 feet in height from the tap hole to the top of the furnace lining, and the capacity of each is 450 tons per day. Each furnace has four blast stoves. The interior diameter of the blast furnace is 15 feet at the hearth, 21½ feet at a height 13 to 21 feet above the hearth, and 16 feet at the top.

FIG. 244. — The Whitwell Hot-blast Stove. (Thurston.)

The earlier blast furnaces were blown with cold air, but later a hot blast was used with an aim to saving fuel, and the air from the blowing engines passed through stoves which were heated by the waste gases from the furnace. Fig. 244 shows the Whitwell stove and Fig. 245 a more modern stove.

The first stoves in use were of cast-iron. The gases were burned around and circulated among U-shaped cast-iron pipes enclosed in a fire-brick structure. This process was continuous — a recuperative process. However, it was

subject to a number of defects, among which was the burning out of the tubes, making it impossible to obtain more than 900° F. in the blast. This type of stove was followed by the fire-brick stove operated on the regenerative principle, and by its use a hot-blast temperature of approximately 1500° F. can be obtained.

The atmosphere is the most variable element involved in the blast-furnace process, which consumes air in large quantities. In furnaces using ore from the Lake Superior district the raw material, amounting to about 7200 pounds per ton of iron, varies in composition within 10 per cent, but the atmosphere, of which 11,700 pounds are consumed per ton of iron, varies in its content of moisture from 20 to 100 per cent from day to day and often in the same day.

Many experiments have been made to determine the most feasible method for extracting the moisture from the air. Various schemes for its direct absorption were worked out and in turn abandoned, and finally Mr. Gayley* designed and put in successful operation the dry-blast process which bears his name. This consists in freezing the moisture out of the air. The Gayley process not only reduces the cost of producing the pig iron, but, which is very much more important, gives a more effective control of the operation and product of the furnace.

FIG. 245. — Julian Kennedy Stove. (Harbison-Walker Refractories Co.)

The product was first put in operation on the Isabella furnaces of the

* The Application of Dry-air Blast to the Manufacture of Iron. James Gayley. Trans. American Institute of Mining Engineers, Vol. XXXV (1905), p. 746.

The Application of Dry-air Blast to the Manufacture of Iron — Supplementary Data. James Gayley. Ibid, Vol. XXXVI (1906), p. 315.

Gayley's Invention of the Dry Blast. R. W. Raymond. Ibid, Vol. XXXIX (1908), p. 695.

Carnegie Steel Company, situated at Etna, Pa., a suburb of Pittsburg, on August 11, 1904. The lines and dimensions of this furnace, shown in Fig. 246, represent the usual construction of furnaces in the Pittsburg district.

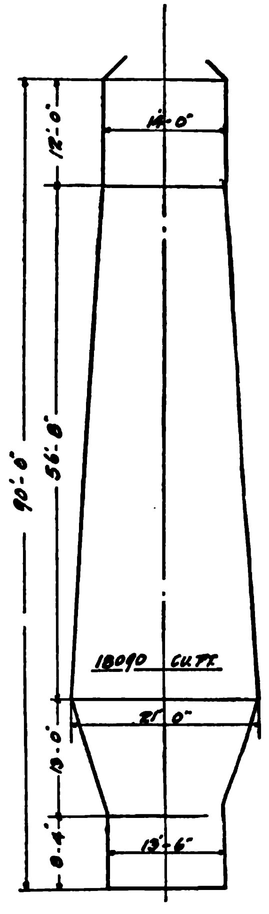


FIG. 246. — Isabella Furnace, Carnegie Steel Company. (Am. Inst. of Mining Engrs.)

Fig. 247 shows graphically the operation of each day, averaged with all the preceding days from August 1 to September 9, 1904, nclusive; the increase in output and reduction in coke consumption corresponding to the increase in burden; the varying conditions of humidity from day to day, which represent the average humidity for each twelve-hour period; and the change in humidity after treatment in the dry-blast apparatus.

The materials for smelting are iron ores, limestone (flux), and fuel. Charcoal was first used and the iron from this fuel was of excellent quality on account of the low ash and sulphur of the charcoal and its great porosity. It has so little strength, however, that its use in the modern high furnaces is prohibited.

Coke is now generally used. Anthracite as a blast-furnace fuel is inclined to decrepitate and give trouble from its fineness. Bituminous coal is not used, as it cakes and absorbs heat for distillation of volatile constituents.

* At Gary, Plate XXIX, between the stock pile and the furnace is a line of elevated storage bins arranged in two parallel rows. One row is for coke and the other for ore and limestone. Above the bins are four tracks on which travel two 60-ton electric transfer cars. The ore is loaded into the transfer cars by the buckets of the overhead ore bridges. The coke and limestone are brought up over the bins by rail and deliver their load directly by gravity.

At the bottom of the bins are spouts controlled by electrically operated gates, and below these are tracks which run the full length of the bins. Traveling on these tracks are electrically operated lorries into which the ore, coke, and limestone are delivered from the bin spouts. The lorries carry the materials to what are known as the "furnace skips," of which there is a pair to each furnace. The skips run upon an inclined railway which runs direct from a pit

* Scientific American, December 11, 1909.

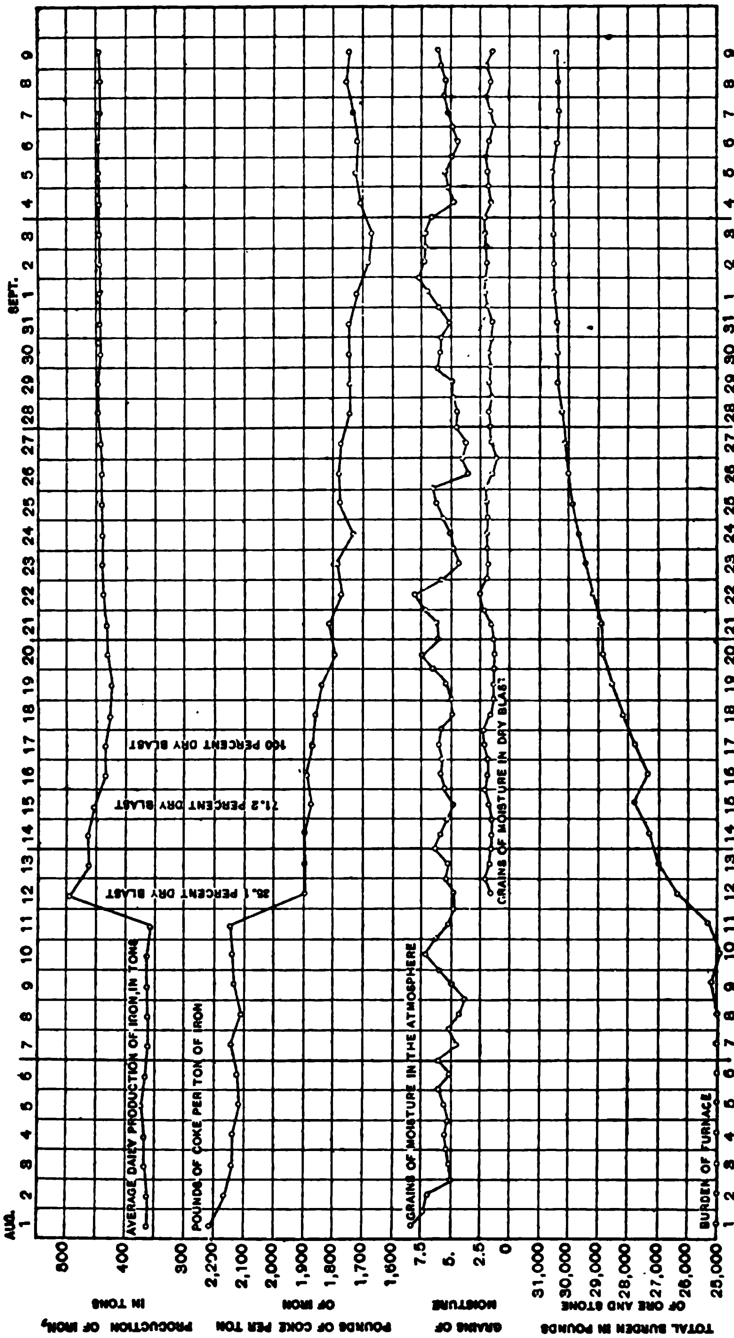


FIG. 247. — Operation of Isabella Furnace on Dry Blast. (Am. Inst. of Mining Engrs.)

below the transfer cars to the charging platform at the top of the blast furnaces.

The operation is entirely automatic. Each trip of the skip is made in about sixty seconds, and its average load consists of about 7000 pounds of ore, or 6000 pounds of limestone, or 3600 pounds of coke.

At Cambria* from the port of entry the ore is hauled to the works and there unloaded by a car-dumping machine, and again handled and stacked by a traveling gantry. From the stock pile it is brought back to special bin cars that are run into the charging house, where they take the place of the usual bins and discharge into hoppers that empty into the loading skips, which are hoisted to the charging door at the top of the furnace.

Slag is run off either continuously or at short intervals. The iron is tapped regularly into a runner, through which it flows either into the molds of the pig-bed or else into the direct metal ladles.

To control the kinds of pig iron produced by a furnace, we can vary the composition of the slag, and change the burden. The burden is made heavy by increasing the amount of ore and flux to a charge.

Mr. Wickhorst† gives the following as the day's burden of "A" blast furnace at the Maryland Steel Company:

	Tons.
El Cuero ore	346.299
Nicolaieff ore	60.676
Sierra Morena ore	17.759
Coke	346.875
Limestone	82.366
Dolomite	82.266

The records of the ore analyses were as follows:

	El Cuero.	Nicolaieff.
	Per cent.	Per cent.
Iron, natural	58.31	65.75
Iron, dried at 212° F.	59.52	66.86
Moisture	2.03	1.66
Silica	9.52	2.16
Manganese	.32	.13
Phosphorus	.017	.017
Sulphur	....	trace

No nickel, cobalt, copper or chromium in either one.

The metal from the blast furnace was poured into an 85-ton receiver, from which it was weighed and poured into an 18-ton converter.

The same authority gives the following for the blast-furnace practices at

* Railway Age Gazette, August 19, 1910.

† Report to Rail Committee, Proceedings Am. Ry. Eng. & M. of W. Assn., Vol. 12, Part 2, 1911.

the Gary works. Lake Superior ore was used, reduced in blast furnaces using ordinary air and having the following average charge:

	Pounds.
Coke	12,000
Stone	5,100
Ore	26,500

hell

FIG. 248.—300-ton Mixer. *E*, Filler; *H*. Pouring Spout. (Harbord and Hall.)

A mixture of ores was used, but consisted largely of Chapin ore, showing analysis as follows:

	Per cent.
Iron	54 63
Aluminum (about)	2.00
Manganese	.21
Phosphorus	.059
Sulphur	trace
Silica (SiO_2)	5.51

The limestone used analyzed about as follows:

	Per cent.
Calcium oxide	54.67
Magnesium oxide	.53
Iron and aluminum oxides	.74
Silica	.68

The iron from the blast furnaces was poured into a mixer, from which it was weighed.

The direct process is one by which the steel is made from the ore in one operation. In ordinary coke blast-furnace practice successive casts vary too much in Si and S to allow of taking the metal as it flows from the furnace into ladles and from them to the converter or open-hearth furnace. It is, therefore, poured first into large reservoirs or mixers, the casts from different furnaces being mixed together.

Capt. Wm. R. Jones was the first to use the mixer in anything like the form which has now become universal practice. He built and successfully operated his mixer at the Edgar Thomson Works, and although it may have previously been used in some modified form the introduction and practical use of the mixer in connection with the Bessemer process is apparently due to his efforts.

The larger the mixer the better are the results obtained, both with respect to the purification and also in retaining the available heat of the metal. Mixers capable of holding 600 tons of metal are now in use. Fig. 248 shows the general arrangement of a 300-ton metal mixer in use at the Cambria Iron Company's Works.

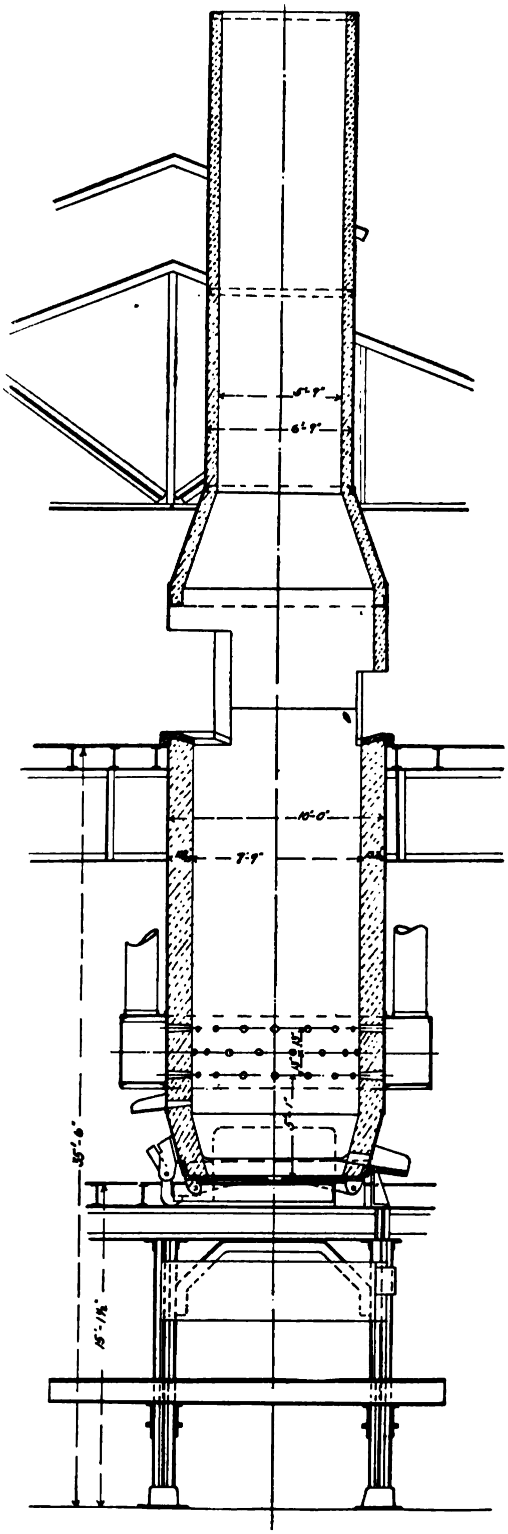


FIG. 249. — Ten-foot Iron Cupola, Maryland Steel Company.

The molten metal for supplying the converter when not taken direct from the blast furnace or the mixer is melted in cupolas. The modern cupola is really a small blast furnace, as shown in Fig. 249.

31. Conversion of the Steel

The principal points in connection with the conversion are given below:

1. The temperature of the conversion must be controlled;
2. The recarbonizer must be thoroughly mixed;
3. Time and opportunity must be allowed for the escape of gases imprisoned in the molten steel.

There are three methods of converting the metal from the blast furnace into steel: the Bessemer converter, the Open-hearth furnace and the Electric furnace. The first or Bessemer process has had an important influence upon railroad history. The out-growth of an attempt to make wrought iron cheaply, it came in just at the time when the wrought-iron rail was beginning to demonstrate its unfitness to stand the increased wheel loads then coming into use. It perhaps is not too much to say that the Bessemer steel rail has made the modern railroad possible, and that without it, or its equivalent, the world's development would be half a century behind its present advanced position.

The pneumatic method of steel making, generally known as the Bessemer process, was until the last few years the most extensively practiced and the most productive, by far, of all known methods of making ingot metal.

* It has been known since the time of Cort that the agitation of molten cast iron in presence of oxygen will produce combustion and removal of carbon, and the reduction of the cast iron to the state of malleable iron or of steel.

The pneumatic process secures such an agitation and a very thorough intermixture of the fluid iron with the oxidizing atmosphere, by causing the latter to stream up through the molten mass in innumerable minute bubbles; the rapid combustion thus secured is sufficient to supply all heat needed, not only to retain the metal in a fused condition, but, also, so rapidly and so greatly to elevate its temperature during the operation that the product, even when entirely deprived of carbon, remains a perfectly fluid wrought iron in the converting vessel.

Fig. 250 shows earlier experiments of blowing air through the bath.†

The process was invented independently by Henry Bessemer, in Great Britain, and by William Kelly, in the United States.

* Iron and Steel, Materials of Engineering, Thurston, New York, Part 2, 1909, p. 241.

† Sketch of the Origin of the Bessemer Process, by Sir Henry Bessemer. Trans. American Society of Mechanical Engineers, Vol. XVIII, 1897, p. 455.

* It is even claimed for America that it was the birthplace of the pneumatic process of steel making, Kelly having begun a series of experiments based upon this theory as early as 1851. As Kelly, soon after Beessmer's patent was taken out, succeeded in showing that he had previously had similar views, Bessemer's patent rights in the United States became limited to certain mechanical arrangements, and a lawsuit arose between the company which bought

FIG. 250. — Early Experiments of Blowing Air through Bath. (Am. Soc. M. E.)

Bessemer's patent rights for that country and that which took over both Kelly's right and Munshet's patent for taking away the red-shortness of the final product by the addition of spiegeleisen. This lawsuit, together with the Civil War, prevented the development of the Bessemer process in the United States up to the year 1866, when an agreement was at last entered into between the two companies.. Both these companies had, indeed, before this time constructed their experimental works; but it was only after the compromise was concluded between the two companies that there could be any steps taken for erecting Bessemer works on a larger scale.

* Steel: Its History, Manufacture, Properties, and Uses, J. S. Jeans, London, 1880, p. 144.

Fig. 251. — Bessemer Steel Works, Johnstown, Pa. (Thurston.)

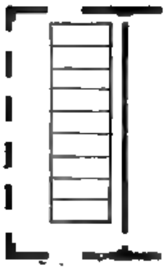


FIG. 252. — Plan. FIG. 253. — Section on Line *HK*.
American 5-ton Bessemer Plant. (Thurston.)

The plant shown by Fig. 251 may be taken as illustrative of an efficient arrangement. The general arrangement of the Bessemer plant is shown in the accompanying drawings. Fig. 252 represents the ground plan as designed by

FIG. 254. — Arrangement of Converters at Maryland Steel Company. (Am. Soc. of Mech. Engrs.)

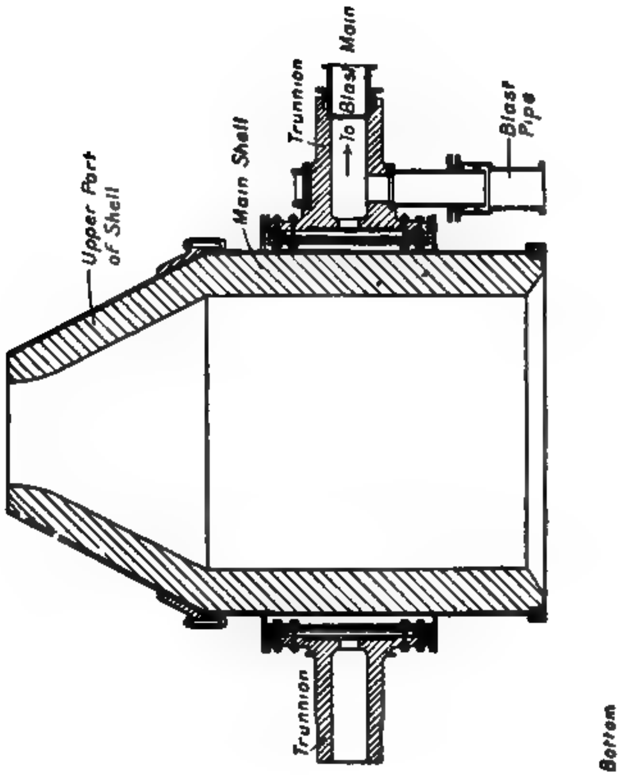
Holly, and Fig. 253 is a section laterally on the center line of the pit surrounding the converter.

The pig iron is melted in cupolas, *A, A, A, A,* Fig. 252 in plan, and seen in elevation in the section resting upon the second floor of the converting house, at the right of the converters, *C, C.* Materials are hoisted from the lower levels by hydraulic elevators placed at each end of the charging floor, the one for fuel, the other for metal.

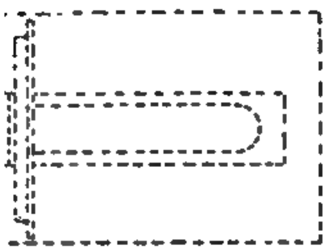
FIG. 255. — 18-ton Converter, Maryland Steel Company. (Am. Soc. of Mech. Engrs.)

Figs. 254 and 255 show 18-ton converters at the Maryland Steel Works, at Sparrows Point, Md., in 1897. Fig. 256 illustrates a typical English Bessemer converter, while Figs. 257 and 258 show converters in operation.

The blow generally requires about ten minutes. The molten iron is poured into the converter when it is lying on its side, as shown by Fig. 257, the converter is then placed in a vertical position and the air, compressed to about 20 pounds per square inch, is turned on, the pressure of the blast being sufficient to prevent the molten metal entering the tuyeres in the bottom of the converter.



Vertical Section of Converter through the Trunnions, showing blast main The bottom section shows the tuyers in position. *KKK*, tuyers; *eee*, rammed ganister.



Elevation of Converter. *N*, brackets and bolts for fastening shell to trunnion ring; *P*, lugs and cottars for fastening bottom section to body of converter; *G*, blast box; *O*, cottars for fastening lid onto blast box.

FIG. 256. — Typical 16-ton Bessemer Converter (Harbord and Hall.)

Fig. 257. — Charging Bessemer Converter. (Am. Tech. Soc.)

FIG. 258. — Bessemer Converter in Full Blast. (Am. Tech. Soc.)

The molten pig iron contains a large proportion of carbon which is almost burned out during the blow. The combustion of this carbon increases the heat of the metal and the flame, shown in Fig. 258, is at first red, but rapidly becomes brighter until it can hardly be looked upon by the naked eye. The sudden dropping of the flame after nine or ten minutes gives evidence that the carbon is almost burned out, and the operator turns the converter down and shuts off the blast. Spiegeleisen or ferromanganese is then added to recarbonize the metal.

Mr. Wickhorst* gives the following description of the process of making Bessemer steel at the Maryland Steel Company: The metal from the blast furnace was poured into an 85-ton receiver, from which it was weighed and poured into an 18-ton converter. In addition to the hot metal from the blast furnace, cupola metal was used, which ordinarily is the same metal that has been run into pigs and then remelted in a cupola, this being necessary when the Bessemer plant cannot take care of all the metal from the blast furnaces. In the case of this heat, two-thirds of the cupola metal was Lebanon iron. The converter charge was as follows:

	Pounds.
Metal from No. 2 receiver	22,500
Cupola metal	18,000
Scrap steel	1,000

After blowing, 4300 pounds of spiegel was added to the converter and 260 pounds ferromanganese and 30 pounds ferrosilicon added to the ladle during the pouring. The analyses of the metal in the converter before starting to blow, and before the addition of scrap and of spiegel, were as follows, special samples being taken for these analyses:

	Converter Metal.	Spiegel	Heat Analysis.
Carbon	3.69	3.92	.51
Phosphorus	.040	.064	.046
Sulphur	.060	trace	.060
Manganese	.24	3.96	.89
Silicon	1.33	.65	.101
Copper	.35	none	.39
Nickel or chromium	none	none	none

The basic open-hearth is rapidly supplanting the Bessemer process. This is probably due to the supply of low phosphorus ores being exhausted and the reduced price of scrap, as on account of the great capacity of the Bessemer process the open-hearth would otherwise have little chance.

* Report to Rail Committee, Proceedings Am. Ry. Eng. & M. of W. Assn., Vol. 12, Part 2, 1911.

The first experiments which eventually led to the development and perfection of the open-hearth process were carried on by Josiah Heath about 1845. Siemens began his experiments about 1861, while at the same time Martin was independently working on the same problem in France. The first open-hearth furnace introduced into the United States for the production of steel was built by Frederick J. Slade for Cooper, Hewitt and Company, then proprietors of the New Jersey Steel and Iron Company, at Trenton, N. J.

This method is sometimes regarded as one of decarburization of cast iron by the addition of uncarborized metal; it must not be forgotten, however, that the carbon and silicon of the molten pig metal are not entirely taken out or neutralized by the addition of the uncarborized metal, but that the oxidizing flame from the gas which is burned in the furnace plays an important part. One of the principal objects in adding a large amount of scrap is to save time and cost of fuel in the decarborizing and desiliconizing process as well as to also save the lining of the furnace.

* The furnace (Fig. 259) consists of a rectangular bath, hearth, or basin, open at each end for the admission of gas and air at the ports. This hearth is arched by a roof from 9 inches to 12 inches in thickness. At each end of the furnace are two checker chambers, one for the preheating or regeneration of the air, the other of the gas. Before starting the furnace a wood fire is built in one set of chambers (or in the furnace) and after these have attained a dull-red heat the gas and air are passed through them, entering at one end of the furnace, are deflected downward by the direction of the ports, unite in combustion over the hearth, and the gases, the products of combustion, leave the furnace through the ports at the opposite end, passing downward through the checkers or regenerative chambers, there giving up their heat to the checkers, thence through the flues to the stacks.

At frequent intervals, say from 15 to 20 minutes, dependent on the quality and amount of fuel, charge, working of furnace, etc., the currents of gas and air are reversed, now entering the furnace at the opposite ends and having passed through the checker chambers, heated up during the previous period, take this stored-up heat to create a more intense flame over the bath. These waste gases in turn pass out through the chambers, giving up their heat. This reversal is maintained with regularity until the charge is ready to tap.

Fig. 260 illustrates the general arrangement of an open hearth plant.

The Talbot continuous open-hearth process employs a tilting furnace which may be operated at a capacity of from 20 tons upward; 100 to 150 or even 200 tons are entirely practicable. The charge is run in from the cupola,

* A Study of the Open Hearth, Harbison-Walker Refractories Company, Pittsburg, 1909.

blast furnace, or mixer, desiliconized wholly and decarbonized largely by a blanket of slag rich in oxides, and reduced ultimately in the usual way. The

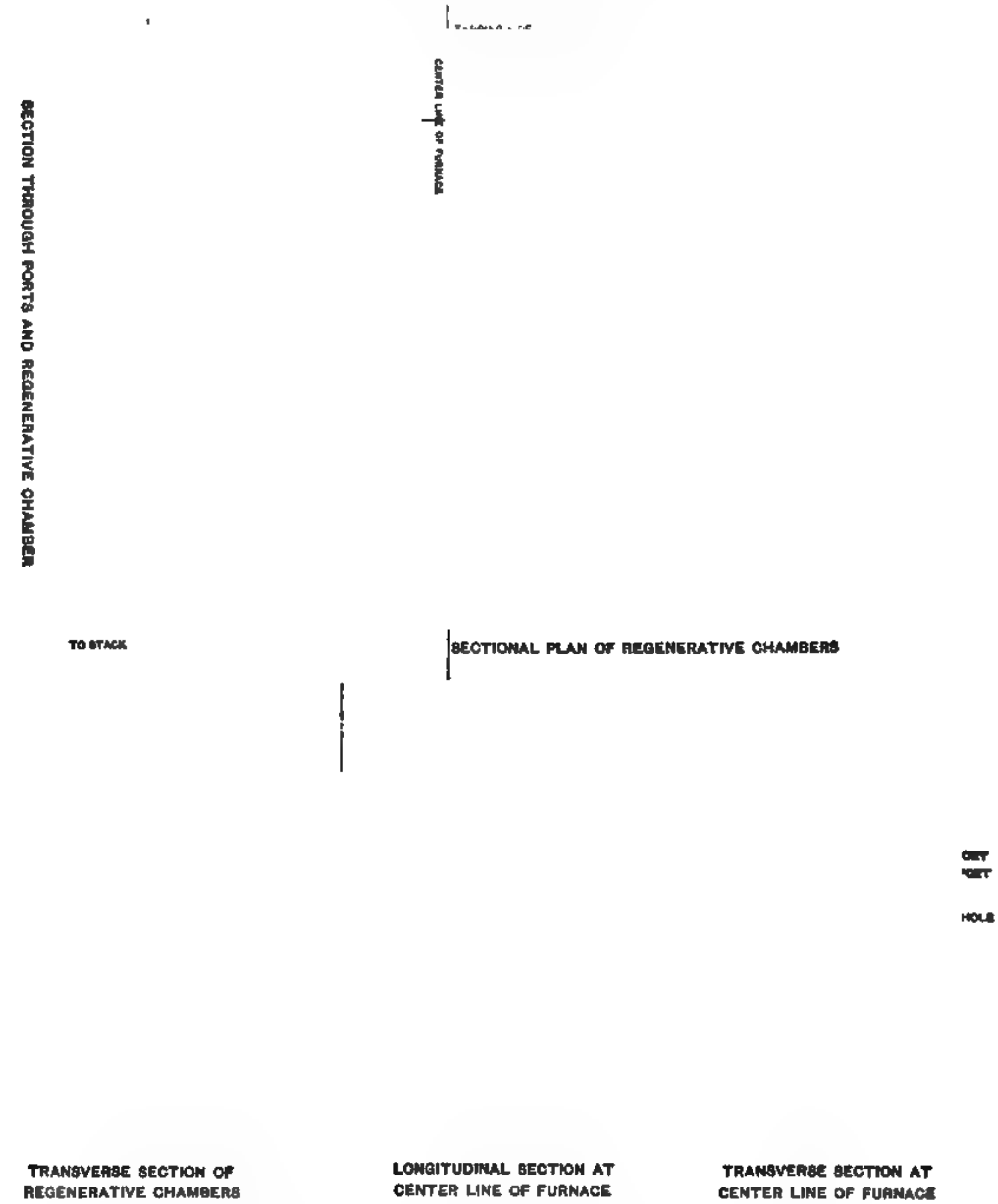


FIG. 259. — Modern Open-hearth Furnace. (Harbison-Walker Refractories Co.)

charge is run off and its place supplied by a new charge, the bottom being at no time allowed to become exposed.

Figs. 261 and 262 show tilting open-hearth furnaces. Fig. 261 shows a Wellman tilting open-hearth furnace and Fig. 262 was taken at the Jones and

Fig. 260. — Open-hearth Plant.

Laughlin Steel Company's plant, where the Talbot open-hearth process is employed. More Talbot tilting open-hearth furnaces have been installed, both in this country and in England, than the Wellman furnace.

The tilting furnaces do away with a great portion of the tap-hole troubles, the taphole being above the metal and slag lines with the furnace in the normal position, and it is consequently only necessary to fill the tap hole with a very light tamping. They also enable the melter to thoroughly drain the furnace bottom of any slag or metal, it being in the stationary furnace often a difficult matter to rabble or splash out all depressions, and any portion of the heat left

FIG. 261. — Wellman Tilting Open-hearth Furnace. (Am. Tech. Soc.)

in such a hole very soon tends to permeate and disintegrate the surrounding bottom

The process of open-hearth steel production* at the Gary works is illustrated by the following description of an open-hearth heat. This consisted of charging limestone and ore into a basic open-hearth furnace heated with producer gas and piling on scrap. The charging was started at 7.29 A.M. After $2\frac{3}{4}$ hours liquid mixer metal was added, and the whole was melted down until

* Report of Tests of Open-hearth Rails — Gary Works. Wickhorst. Proceedings Am. Ry. Eng. & M. of. W. Assn., Vol. 12, Part 2, 1911.

the tapping test showed carbon .26 per cent by fracture. During the melting small quantities of fluor spar were added at intervals to make the slag more fluid and assist in the melting. The additions of fluor spar started at 2.50 P.M. and amounted to about 1300 pounds total. At 3.00 P.M. a furnace sample was

FIG. 262. — Pouring Steel into Ladle of Open-hearth Furnace. (Copyright, Keystone View Co.)

taken and the phosphorus found to be .012 per cent. At 4.25 P.M. 150 pounds of ore was added. Mixer metal to recarbonize was added to the furnace at 5.02 P.M. The furnace was tapped at 5.12 P.M. and ferromanganese (80 per cent) and ferro-silicon (50 per cent) were added to the ladle, shortly after tapping.

The amounts of the various materials used were as follows:

	Pounds.
Limestone	25,000
Ore (Chapin)	15,000
Scrap steel	60,400
Mixer metal, first charge	110,900
Mixer metal to recarbonize	24,000
Ferromanganese	1,000
Ferrosilicon	500

A sample of the mixer metal used to charge the furnace gave the following analysis:

	Per cent.
Carbon	3.85
Silicon	1.73
Manganese	1.50
Phosphorus	.215
Sulphur	.030

(The silicon in the mixer metal ordinarily averaged about 1.25 per cent instead of 1.73, as shown above.)

The ferromanganese and ferrosilicon had compositions about as follows:

	Ferro-manganese.	Ferrosilicon.
	Per cent.	Per cent.
Manganese	80.0	.3
Silicon	1.0	54.0
Carbon	6.5	.3
Phosphorus	.3	.02
Sulphur	.04	.02

* The hot metal is tapped from the blast furnaces into 40-ton ladles, in which it is hauled to two 300-ton mixers. The metal is poured from the mixers into 60-ton charging ladles, in which it is conveyed to the open-hearth furnaces on electric transfer cars. From these cars the ladles are picked up by a 75-ton traveling crane and the metal is poured into the open-hearth furnaces through a runner (Fig. 263).

The fact that the Bessemer process has already passed the zenith of its growth is one which has now become well recognized by metallurgists generally.

Mr. Talbot has given a very clear presentation of this subject and the author is indebted to him for the abstract of his paper which follows.†

The three main causes bringing about the supersession of the Bessemer process are: 1. The ever-growing scarcity of iron ores suitable either for the acid or basic Bessemer process; 2. The superiority of the product obtained

* Scientific American, December 11, 1909.

† Benjamin Talbot, in the London Times Engineering Supplement, February 13, 1907.

by the open-hearth processes of manufacture; 3. The cheapening of the production of the steel ingot by modern open-hearth methods of manufacture.*

The increasing scarcity of iron ores suitable for use in the acid Bessemer process is, perhaps, the most cogent of the three causes named. In the United

FIG. 263. — Charging Platform of the Open-hearth Furnaces at Gary. (Scientific American.)

States, apart from the Southern States and the northern portion of New York State, there are practically no ores at present available for the manufacture of pig iron suitable for the basic Bessemer process. The rivalry is, therefore, between the acid Bessemer and the basic open-hearth. The former had a long lead, but the growth of the open-hearth rail manufacture has been rapid and in the immediate future the development of the open hearth will be out of all proportion to the further development of the acid Bessemer process.

† The total annual capacity for the production of open-hearth rails in the

* The cheapening of the cost of scrap, while not mentioned by Mr. Talbot, has been an important factor. It should also be observed that open-hearth rails are subject to the same mechanical defects as Bessemer rails, and it has not yet been proved that their superiority over Bessemer rails is very marked; in fact, some extremely poor open-hearth rails have been made.

† Railway Age Gazette, March 16, 1910, daily edition.

United States is now about 1,500,000 tons, the principal mill being that at Gary, which is turning out 500,000 tons; then Ensley, with 400,000 tons; Bethlehem, 200,000 tons; Colorado, 200,000 tons; Lackawanna and others of smaller capacity, 200,000 tons. The total capacity of all mills making open-hearth rails up to 1907 was less than 200,000 tons, and in that year production reached 253,629 tons. In 1908 it reached 571,841 tons, and in 1909, 1,256,674 tons.

The production * of open-hearth steel rails in 1910 was 1,715,899 tons, against 1,256,674 tons in 1909. The increase in 1910 over 1909 was 459,225 tons or more than 36.5 per cent, while the increase in 1909 over 1908 was 684,833 tons or over 119 per cent.

The production of Bessemer steel rails in 1910 amounted to 1,917,900 tons, against 1,767,171 tons in 1909, an increase of 150,729 tons or over 8.5 per cent. Included in the total for 1910 is 68,497 tons of re-rolled rails. In 1911 the production of open-hearth steel rails was less than in the previous year, but on account of the smaller tonnage of Bessemer steel rails rolled than in 1910 more rails were made from open-hearth steel than Bessemer.†

Table LXXXIX gives the production from 1907 to 1911.

TABLE LXXXIX. — PRODUCTION OF STEEL RAILS IN THE UNITED STATES FROM 1907 TO 1911.

	1907.	1908.	1909.	1910.	1911.
	Tons.	Tons.	Tons.	Tons.	Tons.
Bessemer rails	3,380,025	1,349,153	1,767,171	1,917,900	1,138,633
Open-hearth rails	253,629	571,841	1,256,674	1,715,899	1,676,923
Total	3,633,654	1,920,994	3,023,845	3,633,799	2,815,556

‡ In any consideration as to the future of the acid Bessemer process in the United States a thorough understanding of the ore situation is essential. As is well known, the Lake Superior, particularly the Mesaba, ores are the mainstay of pig-iron production in the north. Each year this ore becomes leaner, and there is a difficulty in keeping the phosphorus content of the pig iron manufactured from it below the .1 per cent of phosphorus which is the standard for Bessemer steel in the United States. Steel made from such pig is dangerously near the limit of safety for some purposes, when it is manufactured by the acid Bessemer process, but when treated in any form of the basic open-hearth process such pig produces a metal of most excellent quality, with phosphorus, when desired, down to .02 per cent, or even less. The carbon content of the steel can also, in the latter class of process, be varied within very

* The Iron Age, February 23, 1911, p. 461.

† Railway Age Gazette, July 19, 1912, p. 125.

‡ Benjamin Talbot, London Times Engineering Supplement, February 13, 1907, daily edition.

wide limits, while it is not so easy to produce .6 to .7 per cent carbon steel in the acid Bessemer process, and even if made, steel with such high carbon and with .1 per cent phosphorus, or thereabouts, is certainly not a material that should be looked upon with favor for rail purposes.

All the facts point in one direction. The Bessemer process, while the actual cost of conversion, apart from the question of waste, is perhaps the cheapest, is yet one which requires, either for acid or basic working, a special quality of pig iron, — a quality which is ever tending to become dearer. The waste of metal in the Bessemer must of necessity be higher than in any form of the open-hearth process, and this fact accentuates the importance of the question of the cost of the pig iron; the higher the price, the greater the cost due to waste. Roughly speaking the loss in a Bessemer is from 8 to 10 per cent and in the open-hearth from 3 to 6 per cent.

The margin for economies in the Bessemer process is less than any which can be made in the basic open-hearth process. Unless a radical change is effected in the operation of the Bessemer furnace, only small further savings appear possible. It is true that in some Bessemer the blowing power is still raised by steam obtained from coal burnt under boilers, but even in cases in which the blowing power is obtained from surplus blast-furnace gas, products are absorbed which could otherwise be economically and usefully employed in creating power for other purposes, if the open-hearth process were employed.

* The electric furnace is rapidly coming into use as an important factor in steel manufacture, and where water power is abundant and fuel is scarce it is extending the boundaries which have for a long time confined the iron and steel districts. Experience with the electric furnace in foreign countries has shown that it will purify the metal to a larger extent than the gas furnace or the Bessemer converter, and it is proposed to use it as an adjunct to the ordinary processes of steel manufacture for the purpose of reducing the amount of phosphorus and sulphur and to deoxidize the bath.

After a careful investigation by its metallurgists, the United States Steel Corporation has decided to use a 15-ton Héroult electric furnace at the South Chicago works. Three-phase alternating current will be used, and it is proposed to refine the blown metal from the Bessemer converter in the Héroult furnace, reducing the percentage of phosphorus and sulphur, and to use the product for high-grade steel rails. The capacity of one furnace is sufficient for the production of 500 tons of steel in 24 hours.

* Railroad Age Gazette, March 12, 1909, and Composition and Heat Treatment of Steel, E. F. Lake, 1910, pp. 42–63.

The Héroult steel-refining furnace is of the crucible type with a tilting rack. The heating is initially effected by means of the electric arc which forms between the surface of the slagging materials which float on the metal bath and the two

Longitudinal Sections A–B and C–D

Transverse Section E–F

Fig. 284. — Héroult Electric Furnace. (Lake.)

massive carbon electrodes which are suspended above it. The impurities of the steel are removed by renewing the slag. The refining operation thus becomes a "washing out" one.

The lining is the same as the basic open-hearth and the phosphorus is first reduced and then the sulphur. Recarbonizing is done in the bath by adding crushed electrodes which are 98 per cent pure carbon.

Fig. 264 shows a transverse section through the pouring spout of the Héroult furnace at La Praz, and also longitudinal sections of the furnace through the roof. The electrodes, of which there are two passing through the roof, are shown at E on the figure. An alternating current at 110 volts is used.

In the Stassano arc furnace the necessary heat is obtained by direct radiation from the arc. It is shown in Fig. 265. Various experiments have been made in this furnace to produce steel direct from the ore, but, owing to the difficulty of controlling the composition of the slags with average ores, the production of steel of any required grade is far from easy.*

† More than 5000 tons of rails have been made from steel from the electric furnace at the Roechling Iron and Steel Company, Voelklingen, Germany. The furnace is of a special combination electrode and induction type, known as the Roechling Rodenhauser, and takes three-phase current at 25 periods. The pig iron is blown in a basic lined Bessemer converter, then transferred to the electric furnace for refining at an expenditure of power of 125 kilowatt hours per ton. Recently some tests have been published, made November 27, 1908. The analysis of the three pieces then tested was as follows:

FIG. 265. — Stassano Electric Furnace. (Lake.)
The furnace is inclined to the vertical and rotated by the mechanism shown below.

	Per cent.
Carbon	0.75
Silicon	0.10
Manganese	0.67
Sulphur	0.044
Phosphorus	0 023

The rails were of flange section, 82.65 pounds to the yard.

* Steel, Harbord and Hall, London, 1911, pp. 261–283.

† Railroad Age Gazette, July 2, 1909.

Physical tests were made on these rails; the pieces have a length between punch marks of 7.94 inches and a diameter of almost 1.0 inch, being .975, .966, .984 respectively. These results are given below:

Number.	Ultimate Stress.	Elongation.	Reduction of Area.
		Per cent.	Per cent.
1	123,341	12.25	21.00
2	126,172	12.25	12.60
3	122,765	13.80	20.40

They show excellent ductility, in conjunction with tenacity.

Fig. 266. — Roechling-Rodenhauser Furnace. (Lake.)

The latest development * in connection with the furnace is its operation by a three-phase current, with a frequency of 50 periods for a 15-ton furnace. Fig. 266 shows this furnace in sectional elevation and plan. It is claimed that a special feature of the furnace is the rotation of the charge due to the presence of a rotatory field, as in an induction motor, which insures an automatic circulation in the bath. The furnace is essentially a transformer with a primary winding *A* round both iron cores *H* of the transformer. The secondaries are two in number; one is the molten bath in the form of an 8, the channel *D*

* Steel by Harbord and Hall, London, 1911, pp 261–283, and The Report of the Canadian Commission appointed to investigate the Different Electro-Thermic Processes for the Smelting of Iron Ores and the Manufacture of Steel in Operation in Europe.

between the two cores being very broad. The other secondary is the copper winding *B*, which is connected with the metal plate *E*.

The electric furnaces, just described, show the three distinct types which are claiming the serious attention of metallurgists. In the present state of

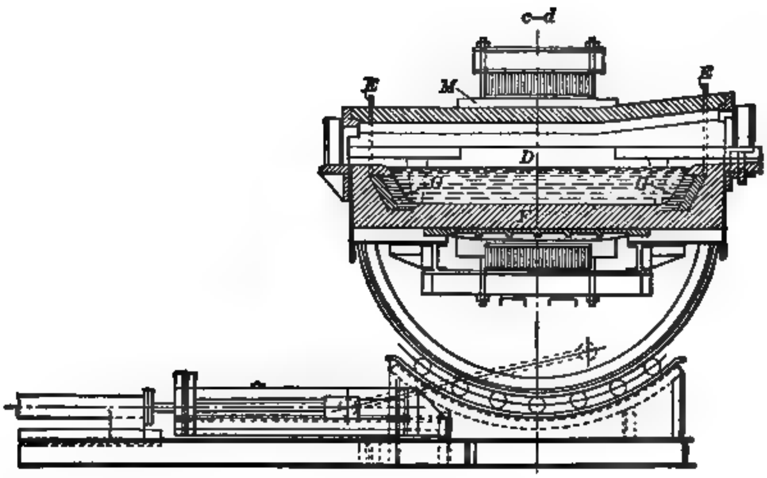


Fig. 266. — Roechling-Rodenhauser Furnace. (Lake). (Continued).

development of the electric furnace it cannot compete as regards cost of production with a modern large open-hearth furnace for the manufacture of rails, and it is only when a superior quality is required that it can be employed.

The steel from different parts of the ingot shows a very regular composition and is remarkably free from segregation of impurities. The mechanical properties are extremely good.

Some recent experiments in the United States show that steel made in the electric furnace has a greater density, and within the range of .08 to .75 carbon, shows 10 per cent greater strength than open-hearth steel of the same chemical composition.

* The duplex process is a combination of the Bessemer and the open-hearth, and is particularly applicable to pig iron containing too high silicon for advantageous working in either basic Bessemer or basic open-hearth.

In the acid Bessemer converter the preliminary blast removes the silicon, together with a considerable portion of the manganese and a certain amount of the carbon. The desiliconized metal is then transferred to the basic open-hearth, where the phosphorus and the remainder of the carbon is eliminated in accordance with the usual practice.

† The Jones and Laughlin Steel Company has been experimenting for some time with the duplex process in its present Pittsburg plant, with the idea of using a portion of its Bessemer capacity for preparing metal for its open-hearth furnaces, thus decreasing its output of Bessemer steel and correspondingly increasing the open-hearth output. The Maryland Steel Company has completed five open-hearth furnaces and is using a considerable portion of its Bessemer capacity to duplex with the new open-hearth furnaces.

These moves in the direction of duplexing represent a distinct desire to find a new use for Bessemer capacity because there is not sufficient employment for it in its old function.

The casting ladle, or the ladle which receives the finished steel for casting into molds, is shown in Fig. 267. If slag is allowed to pass into the ingot molds with the steel the latter is liable to be spoiled, and in consequence the steel cannot be poured from a lip into the molds, but has to be tapped or teemed from a hole in the bottom of the ladle.

The time allowed after the conversion of the steel and when it is held in the converter or casting ladle exercises considerable influence upon the finished product. The thorough mixing of the recarbonizer, and the opportunity for the impurities to separate from the metal and the gas to escape from the molten steel are of importance. Dr. P. H. Dudley requires a definite interval of time between the additions of the spiegel and the teeming of the steel.

He says:‡ " Restricting the ingots to three-rail lengths and holding the steel three minutes after recarbonizing, in connection with the dry blast at South

* A Study of the Open-hearth, by Harbison-Walker Refractories Company.

† Railway Age Gazette, March 18, 1910, daily edition.

‡ Proceedings American Society for Testing Materials, Vol. VIII, 1908, p. 112.

Chicago, shows a marked reduction in seams and cracks in the bases of rails. In a lot of 2500 tons of these rails hardly a trace of seam has been found."

The dry blast referred to is the Gayley process of furnishing air, practically free from aqueous vapor, to the converters while blowing the charge. This

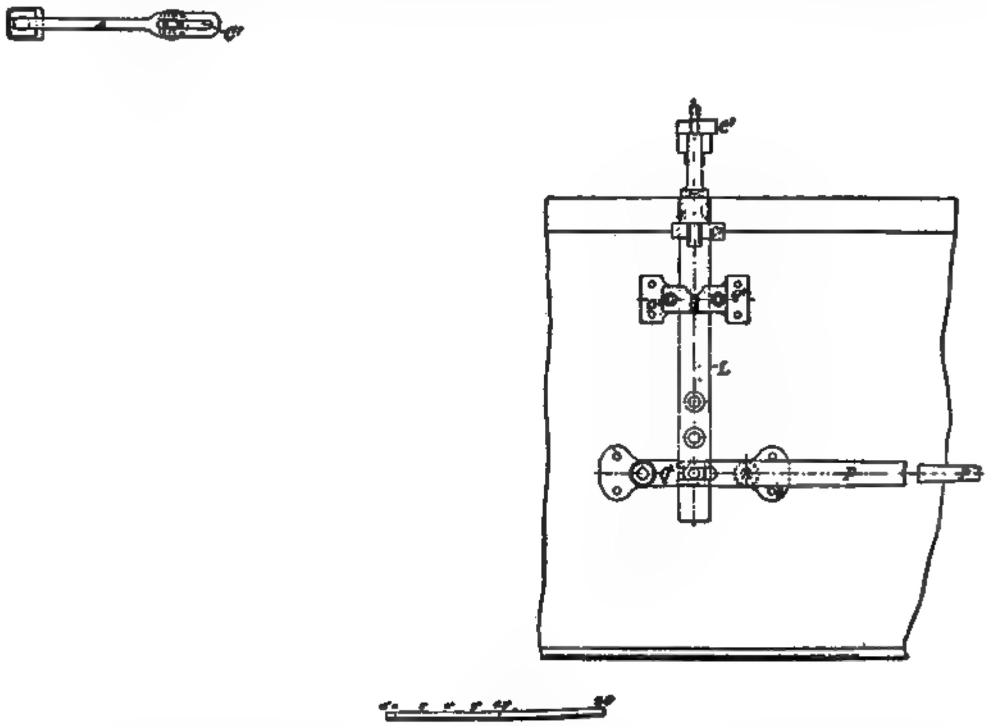


FIG. 267. — Details of Casting Ladle. (Harbord and Hall.)

A, Goose-neck; *B*, stopper rod; *L*, sliding bar carrying goose-neck; M, M^1, M^2, bolts for attaching lever, *P*; *P*, lever bar; Q^1, Q^2, brackets on ladle to guide sliding bar, *L*; *K*, screw bolt for holding sliding bar rigidly in position previous to teeming; *F*, fire-clay sleeves threaded on steel stopper rod, *B*; *Z*, teeming nozzle; *E*, fire-clay stopper head; *G*, nozzle box; *H*, trunnion; C^1, C^2, C^3, C^4, cotter pins; *S*, forged head on sliding bar through which end of goose-neck is passed, and is fixed by cotter pin, C^4.

decreases the amount of iron oxide in the bath which von Maltitz claims to be a principal agent in producing blowholes.

That time should be given for the necessary chemical reaction after the addition of the recarbonizer and before casting the metal into ingots, has been known for at least thirty years. It was known that such time was also important for the escape of the occluded gases, and the value of this latter knowledge was manifested by the several devices for accelerating their escape which, years ago, were either proposed or actually used. These ranged from the thrusting into the ladle full of molten steel a wooden pole, or placing in the ladle before it received the steel from the converter pieces of wood saturated with kerosene, to more elaborate devices, for agitating the steel while in the casting ladle by

power-driven, refractorily protected screws. It was the practice at some of the Bessemer works to again put on the blast after the introduction of the recarbonizer, and then to partially turn the vessel up, thus agitating the charge.

Mr. Robert Forsyth sought to accomplish the desired results through his transferring ladle arrangement, by which the ladle after receiving the steel from the converter was transferred by a hydraulic ram from the receiving crane to the ladle or casting crane. This he did when remodeling the Union Steel Plant, Chicago, about 1886. Later he put the same arrangement in the South Works of the Illinois Steel Company. Later Mr. William R. Walker carried this further by pouring the steel over the top of the receiving ladle into the casting ladle through a nozzle in the bottom of which it was cast in the usual way.

Prof. Henry Fay * has observed the moon-shaped fractures in the base and the thermal cracks in the head of the rail which he believes to be generally found along a streak of manganese sulphide, extending in the direction of the rolling. The cause of the manganese sulphide being in the steel he infers is probably the lack of time given for the steel to purify itself after the addition of the recarbonizer. When the spiegel or ferromanganese is added to the bath, the manganese combines with the sulphur, and, given time enough, manganese sulphide, having a specific gravity less than that of steel, will rise to the surface.

Manganese sulphide melts at 1162° C. Its specific gravity is 3.96, or about half that of steel. It is a glassy, hard, and extremely brittle material. The steel from which the rail is made solidifies at about 1450° C., and the manganese sulphide will not solidify until it reaches 1162° C. Therefore, the manganese sulphide is in a fluid state some time after the steel solidifies. If the rolling of the rail starts, we will say, at a temperature above 1162° C., this material will be rolled out in thin strips in the direction of rolling. It is plastic below the melting point and it is capable of being rolled out while in the plastic condition into long, thin strips.

He states: † "That manganese sulphide when existing in certain forms is a harmful constituent of steels can no longer be doubted. The remedy seems to be a very simple one. Specifications should be so drawn as to limit the amount of sulphur in the steel. At the present time most of the specifications do not even mention sulphur. Having done this, the next step is to allow the metal to stand a longer time after the addition of the ferromanganese. With the

* Journal Association of Engineering Societies, July, 1908, p. 28.

† A Microscopic Investigation of Broken Steel Rails; Manganese Sulphide as a Source of Danger. Fay. Vol. VIII (1908), Proceedings American Society for Testing Materials. Further Investigations of Broken Steel Rails, Fay and Wint, ibid., Vol. IX.

specific gravity of manganese sulphide 3.966 and steel 6.82, it should rise to the surface and be skimmed off with the slag if given sufficient time. Usually this time interval between charging of the ferromanganese and the pouring of the ingot is very short. The desire of the manufacturer to increase his output has led him to cut down this interval to the shortest possible limit, with the natural consequence of a large number of defective rails. A longer time interval will allow the metal to purify itself."

Mr. E. von Maltitz* found that where recarbonizing is done in the ladle and insufficient time allowed for the complete reduction of the iron oxide in the bath, an excessive number of gas holes may be formed. The presence of gas seams tends to cause unsound metal. Mr. Robert Job has pointed out that in nearly every case of failure due to crushed heads the section shows marked unsoundness, and the vertical flaws of the gas seams weaken the head greatly.

The fact should be emphasized that it is not alone sulphide of manganese which is a source of danger, but other forms of slag are also to be looked upon with suspicion.† These may be summed up as follows:

1. Excessive slag (manganese sulphide, silicate, etc.).
2. Segregation of slag concentric with the section.
3. Remnants of slag in the large split portion of the head.
4. Slag in those areas where flow of metal has occurred, or where microscopic cracks have developed.

The rails illustrated in Figs. 268 and 269 show the effect of unsound metal in the head of the rail. Referring to Fig. 268, view 1 shows a section of the rail which has been polished and etched with acid. It shows some segregation and flow of metal, as expected from the rolling. The rail was slivered, breaking off the right of the head as indicated. This view shows also the portions into which this section was cut and the marks by which they are identified; these were in part polished and examined microscopically for defects as shown in the other views of this figure.

View 2 shows the grain size at the center of the head and view 3 shows the finer grain near the surface and the distortion of the grains by wheel action. The photograph is taken at the end of a crack, and shows, besides this, some

* Blowholes in Steel Ingots. E. von Maltitz. Trans. American Institute of Mining Engineers, Vol. XXXVIII (1907), p. 412–447.

† Iron and Steel Magazine, August, 1905 (Job); and Journal of the Iron and Steel Institute, p. 301, 1905 (Captain Howorth).

small cavities, which were more noticeable before etching, and which might have been minute oxide pits or pockets.

View 4 shows the metal, which is the white ground mass, to be badly contaminated by slag, which is extended longitudinally by the process of rolling. These slag lines were found to some extent over the whole surface of this piece, but were worst in the neighborhood of the point indicated by the dot *By*, view 1. This is shown on the picture, which was taken at the edge of the localized portion.

View 1. View 2. Cross Section at point C_s, Mag. 100, 68,000 grains per sq. in.

FIG. 268. — Crushed Head.

Fig. 269 illustrates another example of a crushed head due to unsound metal. View 1 shows a section of the head taken at the point of greatest distortion. The cavity in the top of this view is a drilled hole. On one side of the head a cavity which did not show on the surface, but indicated marked breaking down of the metal, was revealed. The metal, however, is more uniform throughout this rail than was the case in the rail of the preceding figure.

View 2 shows the grain at the center of the head; view 3, like view 3 of Fig. 268, is taken at the end of the crack. It shows the finer grain and distortion of the same, and shows as well the further distortion of the metal at the

end of the crack as a sort of tearing action. The end of the crack is at the corner of the picture; the further direction of progress of the failure is shown by the black defects extending across the photograph.

A longitudinal section of this rail made on portion *G* showed slag lines, as in the rail of Fig. 268, somewhat most abundant at the point *q*, though the number was not so great as in the rail of the preceding figure.

View 3. Cross Section of point H_{10}, Mag. 100.

View 4. Longitudinal Section on Top of Portion B, Mag. 50, Unetched.

Fig. 268. — Crushed Head. (Continued.)

* The deleterious influence of slag inclosures in steel has perhaps escaped attention to some extent owing to the fact that in ordinary tensile tests, taken in a direction parallel to that of rolling, these inclosures only occupy a very small proportion of cross-sectional area and possess a tapered shape which allows of gradual distribution of the stresses imposed on the material. If, however, we consider the case of transverse stresses, or of shock or vibration, it will be seen that these inclosures will be fractured as soon as the metal undergoes any material deformation, and then each such inclosure practically represents an internal

* "Slag Inclosures" in Steel, by Walter Rosenhain. International Association for Testing Materials, 5th Congress, Copenhagen, 1909. McGraw-Hill Book Company, New York.

View 1.

View 2. Cross Section at point C_r, Mag. 100, 95,000 grains per sq. in.

View 3. Cross Section at point H_p, Mag. 100.

FIG. 269. — Crushed Head.

fissure which is ready to extend — and actually does extend — in any direction compatible with the applied stresses.

FIG. 270. — Teeming Ingots at Bessemer Converter. (Copyright, Keystone View Co.)

32. THE INGOT

The principal points in connection with this part of the process are as follows:

1. Care must be exercised in casting the ingot.
2. The ingot must be in a perpendicular position until the interior has had time to solidify.
3. The steel must not be overheated in the heating furnace or soaking pits.
4. Defective material from the top of the ingot must be excluded from the finished product.

From the casting ladles the steel is run into cast-iron ingot molds located on cars, as illustrated in Figs. 270 and 271. Table XC presents data showing the time required to pour the steel at different mills. After solidifying, the

FIG. 271. — Teeming Ingots at Open-hearth Furnace. (Copyright, Keystone View Co.)

ingot mold cars are run under the stripper, shown in Fig. 272, from which hooks are lowered and engage the lugs on either side of the mold and lift it off the ingot.

The ingot is then taken up by a traveling crane and conveyed to the reheating furnaces or soaking pits, shown by Figs. 273 and 274, to allow the temperature in all parts of the ingot to become equalized before rolling.

Fig. 272. — Stripping the Mold from Ingots. (Lake.)

Fig. 273. — Soaking Pits — Gary. (Scientific American.)

English Vertical Coal-fired Ingot-heating Furnace.

American Vertical Gas-fired Ingot-heating Furnace.
FIG. 274.—Soaking Pits. (Harbord and Hall.)

TABLE XC. — TEEMING PRACTICE AT AMERICAN RAIL MILLS

(Compiled by Committee on Rail, Am. Ry. Eng. Assn., 1909, and revised by the author 1912)

Rail Mill.	Location.	Weight of Metal in One Melt.	Time in Pouring into Ingot Molds.	Tons Poured per Minute.
		Tons.		
†Algoma Steel Co.	Canadian Soo, Can.	Bess. 5	4 min.	1.25
		O.H. 40	20 min.	2.0
*Bethlehem Steel Co.	Bethlehem, Pa.	50	20 min.	2 5
*Cambria Steel Co.	Johnstown, Pa.	12	6 min. 30 sec.	2.15
Carnegie Steel Co.	Braddock, Pa.	15	7 min. 15 sec.	2.07
*Illinois Steel Co.	South Chicago, Ill.	13	9 to 11 min.	2.1 to 1.18
†Indiana Steel Co.	Gary, Ind.	80	20 min.	4
*Lackawanna Steel Co.	Buffalo, N.Y.	12	3 min. 15 sec.	3 6
*Maryland Steel Co.	Sparrows Point, Md.	15	6 min.	2.5
Tenn. Coal, Iron & R.R. Co.	Birmingham, Ala.	100	†20 to 25 min.	†4 to 5

NOTE. — Information from R. W. Hunt & Co., except that marked (*), which was obtained direct from manufacturers by the committee.
† Compiled by author.

The unsoundness of the ingot results from several causes:

1. A funnel-shaped cavity or pipe at the top of the ingot.
2. Dispersed cavities or blowholes throughout the ingot.
3. Segregation of the impurities of the steel, as silicon, phosphorus, manganese, etc., from the mass of the metal and their concentration in different parts of the ingot.

The pipe is due to the contraction of the interior of the mass after the outside has set. After molten steel has been cast into an iron mold, the metal in contact with the bottom and the sides begins first to solidify. After a relatively short while the top of the ingot, which is exposed to the cooling action of the air, also becomes solid and the ingot now consists of a rigid metallic shell holding a mass of molten steel, as shown in Fig. 275. As the cooling proceeds this solid shell increases in thickness; but since steel, like most substances, undergoes a considerable contraction in passing from the liquid to the solid state, the mass of metal which when liquid was sufficient to fill the space within the solid shell will, after it has in turn solidified, be unable to fill it and a cavity must necessarily be formed in the upper part of the ingot.

FIG. 275. — Formation of Pipe in Ingot.

The piping of ingots has been known for a number of years.* Robert Forsyth at the Union Steel Works in 1888 demonstrated the relation of the length of the pipe to the position of the ingot while its interior metal was solidi-

* The Manufacture of Bessemer Steels by R. W. Hunt, Lecture delivered at The Franklin Institute, January 21, 1889. See Journal of the Franklin Inst., May, 1889.

fying, by breaking a number of ingots which had been differently handled — some placed in a horizontal position as soon as possible after being cast, and

FIG. 276. — Section of Ingot, 17 ins. Square at Top, 19 ins. Square at Base, and 50.5 ins. long, Containing Cavity of 128 cubic inches. (Am. Inst. of Mining Engrs.)

FIG. 277. — Bloom from an Ingot of same Heat and of same Size as Fig. 276, showing Reduction of Cavity. (Am. Inst. of Mining Engrs.)

others so placed at varying intervals up to having been kept vertically until all of the steel was thoroughly set.

The best modern practice is to charge the hot ingots into the reheating furnaces to equalize their heat for blooming as soon as possible after they are teemed, stripped, and weighed.

An interesting experiment was tried by Dr. P. H. Dudley to determine

the relation between the pipe in an ingot which had been allowed to get cold and one which had been promptly charged into the reheating furnace.*

Fig. 276 is a photograph of a three-rail ingot, for 100-pound rails, teemed in a mold 19 inches square on the base, 17 inches square on the top, and 66 inches long. The ingot, poured 50.5 inches long, was well deoxidized, and therefore had a large cavity. The ingot had a volume of 7.4 cubic feet, inclosing a shrinkage cavity of about 128 cubic inches, practically 1 per cent of its volume. This is a larger percentage than would be found in rail steel not so well deoxidized, or which contained numerous blowholes.

Fig. 277 is a photograph of the bloom of an ingot of the same heat and length, cut for a 9 per cent mill discard. The ingot, after stripping and a subsequent ride of 500 feet, was charged directly into the reheating furnace without allowing the temperature to fall below the recalescence point, while the bulk of the steel was several hundred degrees above, and in about 2 hours the ingot was drawn and bloomed. The cavity was small and less than one-tenth of that of the cold ingot of the same heat.

Blowholes generally form in the upper half of the ingot, which is permeated by honeycombs or dispersed cavities, due to the liberation of imprisoned gases, principally hydrogen, as well as nitrogen and carbon monoxide. These gases are absorbed, dissolved, or occluded in the molten steel, but are wholly or partially evolved and collect into bubbles when the metal begins to solidify. These bubbles are generally more numerous towards the side of the ingot.

The evolution of the gases in the mold seems probably to be due to two causes: First, by the reduction of the temperature, the solvent power of the steel for the gases is lowered and, consequently, certain proportions of the gas are liberated; and, second, an evolution of carbon monoxide (CO) or carbon dioxide (CO_2), due to chemical action.

† According to Howe, blowholes may be lessened or even wholly prevented by adding to the molten metal shortly before it solidifies either silicon or aluminium, or both. An addition of manganese has a like effect.‡ These additions seem to act in part by deoxidizing the minute quantity of iron oxide and carbonic oxide present, in part by increasing the solvent power of the metal for gas, so that even after freezing it can retain in solution the gas which it had dissolved when molten. But, since preventing blowholes increases the volume of the pipe, it is often better to allow them to form, but to control their posi-

* Discussion of Henry M. Howe's paper on Piping and Segregation in Steel Ingots, Trans. American Institute of Mining Engineers, Vol. XL (1909), pp. 821–830.

† Iron, Steel, and Other Alloys, Howe, 1903, pp. 369–372. Contains record of Brinell's experiments.

‡ Titanium deoxidizes the steel in a very marked manner, as shown in Fig. 285.

tion, so that they shall be deep-seated. In case of steel which is to be forged or rolled, this is done chiefly by casting the steel at a relatively low temperature, and by limiting the quantity of manganese and silicon which it contains.

Brinell finds that, for the conditions which are normal at his works at Fagertsa, Sweden, if the sum of the percentage of manganese plus 5.2 times that of the silicon is as great as 2.05, the steel will be so completely free from blowholes as to have an undesirably large pipe. If this sum is 1.66, there will be just that small quantity of minute, hardly visible blowholes which, while sufficient to prevent any serious pipe, is yet harmless. If this sum is less than 1.66, blowholes will occur and will be injuriously near the surface unless this sum is reduced to .28. He thus finds that this sum should be either about 1.66, so that the quantity of blowholes shall be harmlessly small, or as low as .28, so that they shall be harmlessly deep-seated.

These numbers must be varied with the variations in other conditions. In general, either a higher casting temperature, or a smaller cross section of the ingots, or the use of hot or that of thin-walled molds, calls for a smaller quantity of silicon and manganese.

Brinell also finds that an addition of .0184 per cent of aluminum is approximately equivalent to the presence of manganese and silicon in the proportions Mn + 5.21 Si = 1.66 per cent; i.e., it unaided gives rise to structure *B* (Table XCI). Naturally, little or none of this aluminum remains in the steel. It oxidizes to alumina, which rises to the surface of the molten metal, or is found lining the walls of the pipe.

Table XCI and Figs. 278 to 284 give some of Mr. Brinell's results.

TABLE XCI. — INFLUENCE OF MANGANESE AND SILICON UPON BLOWHOLES AND PIPES

(Brinell, loc. cit., p. 370.)

Name of Structure.	Mn + 5.2 × Si.	Position, etc., of Blowholes.	Quality of the Steel as Regards Blowholes and Pipes.
	Per cent.		
A	2.05	No blowholes, but a small pipe.	Injured by the pipe.
B	1.66	No visible blowholes, no pipe.	Just compact enough; excellent.
C	1.16	External blowholes, no pipe.	Injured by the external blowholes.
D	.50	Fewer blowholes and somewhat deeper seated.	Blowholes still harmfully near the surface.
E	.28	The blowholes are very deep-seated.	Excellent.
O	Cast too hot	Many external blowholes and a pipe.	Injured by the external blowholes.
H	Cast too cold	Many blowholes, both external and internal.	Injured by the external blowholes.

The structures *O* and *H* are those induced by too high and too low a casting temperature respectively. The steel which here has structure *O* would, if cast at a normal temperature, have had structure *A*. It was thought that the reason

Fig. 278. — Structure A. — Brinell's Tests.

Fig. 279. — Structure B. — Brinell's Tests.

Fig. 280. — Structure C. — Brinell's Tests.

Fig. 281. — Structure D. — Brinell's Tests.

Fig. 282. — Structure E. — Brinell's Tests.

Fig. 283. — Structure O. — Brinell's Tests.

Fig. 284. — Structure H. — Brinell's Tests.

why the excessively high temperature caused these external blowholes was that it caused the carbon of the molten steel to react on the iron oxide on the surface of the mold, with the formation of carbonic oxide gas, which itself forms these blowholes.

Von Maltitz* gives the following as the means for the prevention of blowholes in steel ingots:

1. Medium temperature of the heat during the last period of the process in the converter or open-hearth.
2. Careful avoidance of overblowing or overoreing of the heat; careful boiling out of the last portion of ore added to the bath.
3. A finishing slag not too rich in oxygen and having the proper degree of fluidity.
4. The destruction, by stirring the heat before tapping, of the ferrous oxide formed.
5. Addition of sufficient deoxidizing material to the heat, and the allowance of sufficient time for the complete separation of the manganese protoxide, silicate of manganese or alumina thus formed, into the slag.

† Howe maintains that the gas contained in the blowholes is partially absorbed and the blowhole walls to some extent weldable during the process of rolling. This action probably is less favorable in direct rolling of rails (i.e., rolling direct from ingot to rail at a single heat) than in reheating practice, in which the bloom into which the ingot is rolled is held in a special bloom-heating furnace before rolling into a rail.

Segregation is one of the important questions before the steel maker. It is, therefore, natural that for many years it should have engaged the attention of iron and steel metallurgists in different countries, and have given rise to an important literature.

Steel contains different impurities, as silicides, phosphides, carbides, sulphides, etc., whose freezing or solidifying points vary, and all have a lower melting point than the metallic iron, consequently those having the lowest melting point will tend to gradually segregate from the iron and concentrate in the hottest part of the ingot. The top and center of the ingot always contains the larger proportions of impurities.

All steels do not necessarily exhibit excessive concentration of impurities.

* Blowholes in Steel Ingots, E. von Maltitz, Trans. American Institute of Mining Engineers, Vol. XXXVIII (1907), p. 445.

† The Welding of Blowholes in Steel, Henry M. Howe, Proceedings American Society for Testing Materials, Vol. X, 1910, p. 168.

The highly segregated portions of an ingot are often very small isolated areas in the interior of the mass.

It is highly probable that a large part of the segregates in steel ingots is directly traceable to the formation of blowholes. The pressure of the cooling gas on the mixture of pure solids and impure liquid in which it forms must squeeze out some of the impure liquid, which passes outward, ascends to the top of the ingot, or finds its way into previously formed blowholes.

Below are presented the results recently obtained by Waterhouse* on segregation in acid Bessemer rail steel. They point in the same direction as those published in 1905 by Talbot, which showed the important influence of aluminium in greatly retarding segregation in certain cases.

In the present instance, titanium, when rightly applied in the proper amount, was also found to retard segregation of sulphur, phosphorus, and carbon, in what is normally quiet, quick-setting steel.

The ingots used were from an ordinary rail-steel heat, and from a heat to which had been added 64 pounds of ferrotitanium, which amounted to only .25 per cent of the weight of the heat. The ordinary steel was made in the usual way. After the heat was turned down, the proper amount of molten spiegel was poured into the vessel. The heat was held there a short time, poured into the ladle, and then through a $1\frac{1}{2}$-inch nozzle into the ingot molds.

There were six molds. After three ingots had been poured a ladle test was taken. The third ingot of the six was allowed to cool while still standing on its stool, and was then cut through longitudinally.

The heat in which ferrotitanium was used was made in exactly the same way. As the steel was poured into the ladle, the alloy was shoveled in; the heat was then held in the ladle for three minutes before pouring the ingots. In this case also the third ingot of the heat was cooled in an upright position and cut through longitudinally. An analysis of the ferrotitanium gave:

	Per cent.
Carbon	10.50
Titanium	11.60
Iron	74.12
Silicon	1.60
Manganese	0.30
Calcium	trace

Photographs of the ordinary and titanium ingots are shown in Fig. 285. The noticeable feature is the increased soundness of the titanium steel, due to the concentration of the blowholes in the pipe cavity.

* The Influence of Titanium on Segregation in Bessemer Rail Steel, G. B. Waterhouse, Proceedings American Society for Testing Materials, Vol. X, 1910, p. 201.

The analyses of the ladle tests from the two heats were as follows:

	Carbon.	Sulphur.	Phosphorus.	Silicon.	Manganese.
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
Ordinary steel	0.44	0.098	0.088	0.117	0 91
Titanium steel	0 47	0 068	0.093	0.118	0.95

Ordinary Steel. Titanium Steel.

FIG. 285. — Ordinary Steel Ingot and Titanium Steel Ingot. (Am. Soc. for Testing Materials.)

No trace of titanium could be found in the latter steel, so that it is not, strictly speaking, a titanium steel, but will be called so for the purpose of distinction.

In the accompanying diagrams, Figs. 286 to 291 inclusive, are shown the results obtained from determinations for sulphur, phosphorus, and carbon. A $\frac{13}{16}$-inch drill was used, and drillings were taken to a depth of $\frac{3}{8}$ inch. The

diagrams are drawn to scale, so that the location of the drillings can be readily seen. The methods used were the same for all the samples and all the determinations were made by one man. The results are briefly considered in order.

Sulphur segregates the most. In the ordinary steel it has risen from .098 per cent in the ladle test to a maximum of .223, and there is a considerable

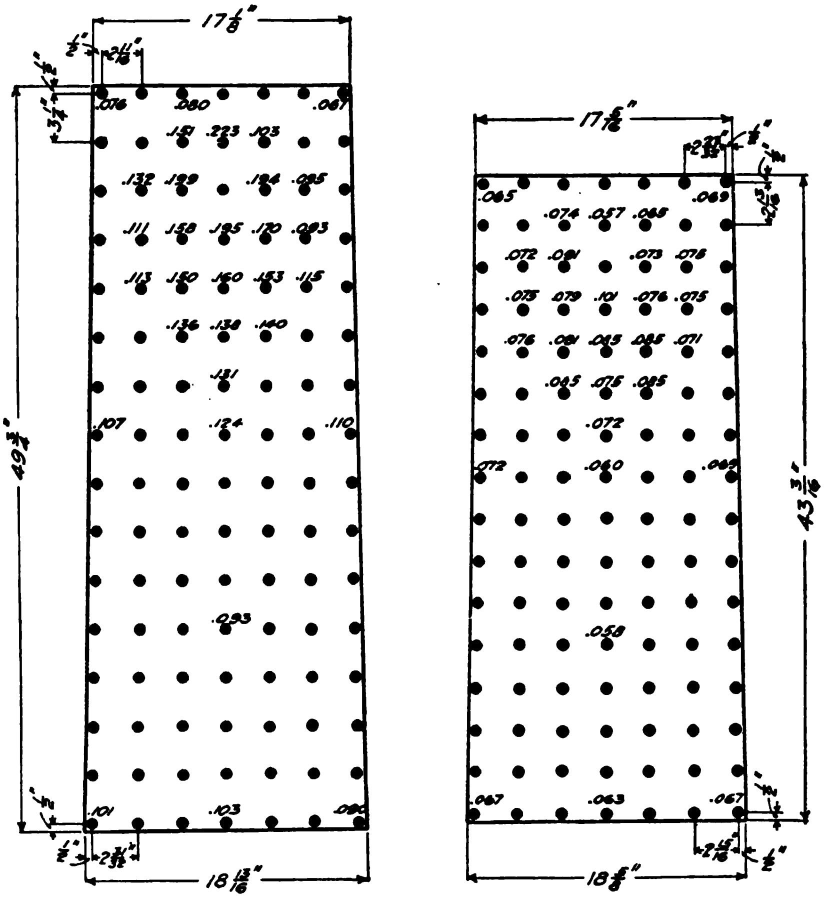


FIG. 286. — Normal Ingot, Half Section. Sulphur in Ordinary Steel.
FIG. 287. — Titanium Ingot, Half Section. Sulphur in Titanium Steel.
(Am. Soc. for Testing Materials — Waterhouse.)

area with more than .147, which is 50 per cent more than the ladle test. In the case of the titanium ingot, the contrast is very remarkable. The greatest result is .101, which is not quite 50 per cent more than the ladle test, .068, and the segregated area is very much smaller than in the case of the ordinary ingot. It is true that there are two factors which may partly account for this difference in results: the titanium ingot is somewhat smaller, and there is less sulphur in the steel as a whole. The fact remains, however, that there is much less segregation of sulphur in the titanium than in the ordinary steel.

In the ordinary steel the phosphorus has risen from .088 per cent in the ladle test to a maximum of .167, and here also the segregated area is seen to be considerable. In the titanium steel the maximum is .124, starting with a ladle test of .093, and the segregated area is more restricted than in the case of the ordinary steel. The ordinary steel is in a better condition to start with

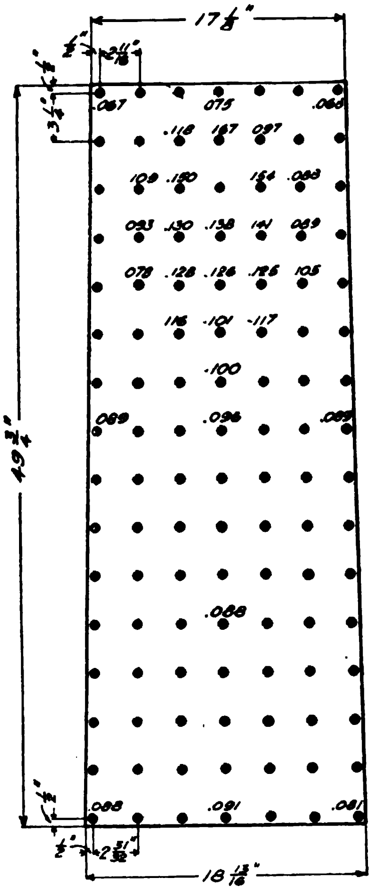


FIG. 288. — Normal Ingot, Half Section. Phosphorus in Ordinary Steel.

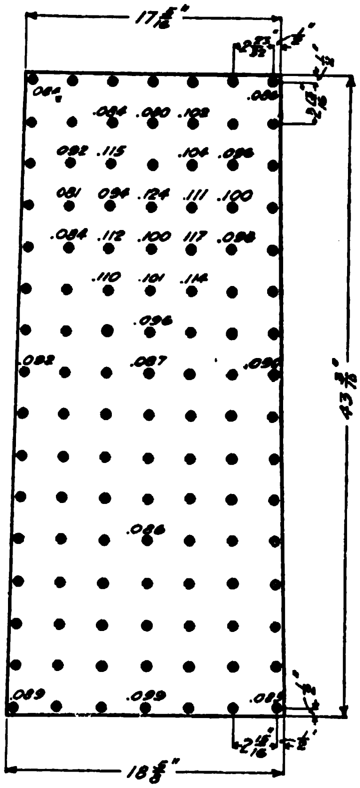


FIG. 289. — Titanium Ingot, Half Section. Phosphorus in Titanium Steel.

(Am. Soc. for Testing Materials — Waterhouse.)

than the titanium steel, as it has slightly less in amount (.088 as compared with .093), so that the behavior of the phosphorus is a good test of the preventive power of the titanium. The results given in the diagrams Figs. 288 and 289 show it to have been effective.

The titanium steel shows less segregation of carbon than the ordinary steel, and it must be remembered that it starts with .47 as compared with .44 per cent. The highest results found are .67 in the one case and .69 in the other,

and the diagrams show that the ordinary steel again has the larger segregated area.

The results of the silicon and manganese determinations are not given; they are somewhat erratic in each case, but do not exhibit segregation.

Mr. Henry M. Howe presented a very complete discussion on Piping and

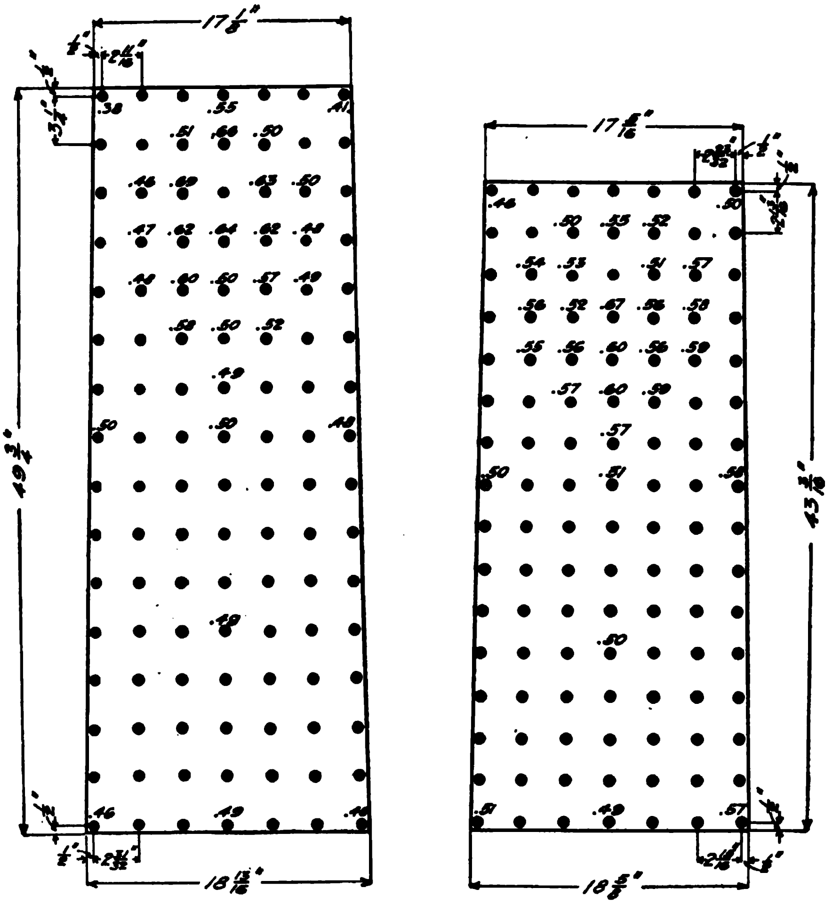


FIG. 290. — Normal Ingot, Half Section. Carbon in Ordinary Steel.

FIG. 291. — Titanium Ingot, Half Section. Carbon in Titanium Steel.

(Am. Soc. for Testing Materials — Waterhouse.)

Segregation in Steel Ingots, at the London meeting (July, 1906) of the American Institute of Mining Engineers,* of which the following is an abstract. The first part of this paper treats of the causes and the restraining of piping in steel ingots, the second considers the causes and the restraining of segregation, and the third proposes certain precautions in engineering specifications concerning these two defects. An article coming from such a source is necessarily of value

* Piping and Segregation in Steel Ingots. Howe, Trans. American Institute of Mining Engineers, Vol. XXXVIII (1907), p. 3-108.

in any consideration of these subjects, and it will be pertinent to briefly review it.

Professor Howe infers that the pipe is chiefly due to what may be called the virtual expansion of the outer walls of the ingot in the early part of the freezing, and finds that the upper and smooth-faced part of the pipe probably forms while the interior is still molten, but that the lower, steep, and crystal-faced part probably forms in metal which is already firm. Of the causes which may coöperate to limit the depth of the pipe, it is suggested that three, namely, blow holes, sagging, and the progress of freezing from below upwards are usually effective.

The pipe may be lessened by casting (1) in wide ingots; (2) in sand molds; (3) at the top instead of at the bottom;* (4) slowly; (5) and with the large end up; (6) by the use of a sinking-head or other means of retarding the cooling of the top; (7) by permitting blowholes to form; (8) and by liquid compression.

It is believed that although the reasons why (1) casting in wide ingots and (2) in sand or clay-lined molds shortens the pipe do not apply to show that they should raise the segregate, yet the position of the segregate should be raised by the six other means by which the pipe is shortened (see 3, 4, 5, 6, 7, and 8 in preceding paragraph).

The means proposed for lessening the degree of segregation, as distinguished from raising the position of the segregate, are next considered.

These are:

9. Quieting the steel by adding aluminium.
10. Casting in small instead of in large ingots, and hastening the solidification, not only by casting in small ingots but also
11. By casting at a low temperature.
12. By casting in thick-walled iron molds (i.e., those of high thermal conductivity); and
13. By casting slowly.

It is pointed out that quieting the steel has materially lessened segregation in certain cases, and that segregation is probably much less in small than in large ingots.

The effectiveness of the different methods of fluid compression (see Figs. 294–297) is considered, and it is concluded that the beneficial lifting effect on the segregate should be the greatest in Williams' system, which compresses the

* Ingots are now practically all cast from the top, absolutely so in regard to rail steel. About twenty years ago there was a great deal of bottom casting practiced, in casting the ingots at the Pennsylvania Steel Company's Works, which were rolled into rails at the Cambria Company's Works, Mr. A. L. Holley first used bottom casting.

ingot chiefly in the middle of its length; it should be the least in Whitworth's system, which compresses the ingot more at its top than elsewhere; and it should be intermediate in the systems of Illingworth and Harmet, which compress the ingot equally in all parts of its length.

Finally, stress is laid on inspection at the rolls and shears, and especially on axial drilling of the billets or other products.

Figs. 292 and 293 * present experimental verification of the following predictions made in this paper:

A. That the pipe is shortened and the segregate raised:

1. By slow casting.
2. By casting with the large end up instead of down.
3. By retarding the cooling of the top, e.g., by means of a sinking head.

B. That the pipe is shortened by slow cooling.

C. That the pipe and segregate lie in the last freezing part.

The procedure was to cast ingots of wax containing a little bright-green copper oleate (usually 1.5 per cent) under varying conditions; to saw each ingot open along a longitudinal plane passing through its axis; and to examine the longitudinal section thus laid bare. The segregated or enriched parts are shown by the darker areas in the photographs, indicating the green of the segregated copper oleate.

Taking up the evidence in detail, the influence of the rate of casting is shown in ingots Nos. 1, 2, and 3, Figs. 1, 2, and 3. The casting of No. 1 was finished in 30 seconds and that of No. 2 was so slow that, though it was continuous except for momentary interruptions for heating the wax, it lasted 1 hour and 13 minutes.

The pipe in the fast-poured No. 1 stretches down 90 per cent of the ingot's length, and, except for some very thin bridges, is practically continuous for 49 per cent; whereas in the slowly cast ingot the pipe stretches down only 14 per cent of the length of the ingot. In this particular ingot (No. 2) there is a second rudimentary pipe near the bottom, caused by the accidental pouring at first faster than was intended. In ingot No. 3, which was poured slowly from the start, this second pipe is absent.

The segregate in the fast-poured ingot No. 1 can be traced at *A* near the bottom of the ingot. The slow-cast ingot No. 2 has a succession of local axial

* The Influence of the Conditions of Casting on Piping and Segregation, as shown by Means of Wax Ingots. Howe and Stoughton, Trans. American Institute of Mining Engineers, Vol. XXXVIII (1907), p. 109.

horizontal segregates, and in the still more slowly cast ingot No. 3 these local segregates are so small as almost to escape notice

The effect of casting with the large end up instead of down is shown in

Fast pouring

Poured fast at first, then slowly.

Poured very slowly.

Large end up

Large end down.

Hot top, fast cooling.

FIG. 292. — Influence of Conditions of Casting as shown by Wax Ingots (Figs. 1–6) (Howe and Stoughton.)

Figs. 4 and 5, which represent two ingots cast in immediate succession and under otherwise like conditions. The pipe stretches down only 30 per cent of the ingot's length when the large end is up, but 82 per cent when the large end is down. The segregate lies well above the center in the ingot with the large end up, but very near the bottom in that with the large end down.

The effect of retarding and of hastening the cooling of the top of the ingot is shown in Figs. 6 and 7 and in Figs. 8 and 9. The depth to which the pipe reaches as a nearly continuous cavity is only 26 per cent of the ingot's length in the hot

Cold top. fast cooling. Cold top. slow cooling. Hot top. slow cooling. Warm top. fast cooling. Warm top. fast cooling. Lateral deflection. Warm side. Cool side. Fast cooling.

FIG. 293. — Influence of Conditions of Casting as shown by Wax Ingots (Figs. 7–13). (Howe and Stoughton.)

topped ingot No. 6, but 85 per cent in the cold-topped No. 7. The pair of ingots Nos. 8 and 9 which were slow cooling do not show so well the influence of the distribution of temperature on the position of the pipe.

The effect of the rate of cooling is shown in Figs. 8, 9, and 10. Figs. 11 and

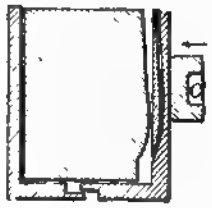
13 illustrate what Professor Howe calls "surface tension bridges." In the middle and lower part of No. 11 there are five bridges from F to J and at K and L, as well as at M of Fig. 13, there are the remains of bridges. These are in each case greener than between the bridges and appear to have been formed on account of

Fig. 294. — Illingworth's Press for Compressing Steel Ingots Horizontally while Solidifying, Sectional Plans.

In I, the mold is shown ready for receiving the molten steel. Two distance-bars, DD, are set between the halves of the split mold B and C. After the steel has been poured into the mold, these distance-bars are pulled out lengthwise, and the two halves of the mold are then forced towards each other by means of the ram F, shown in II. The convex edges of the distance-bars are for the purpose of making an initial depression in the side of the ingot lest part of its side should be forced out as a fin or welt into the crevice between the two halves of the mold.

(Trans. Am. Inst. of Mining Engrs., Vol. XXXVIII.)

the local enrichment of the oleate, making the wax so fusible and plastic that it stretches instead of cracking open when the pipe is being formed. The same phenomena was noticed at E, F, G, of Fig. 12. The ingot of this figure had its cooling



I II III

Fig. 295. — Williams' Abdominal Liquid Compression of Solidifying Steel Ingots.

The ingot is cast in its mold as shown at I. After its outer crust has solidified the mold is opened, as shown at II, and a liner B is slipped between mold and ingot. A strong cap A is then fastened down, and by means of pressure applied through the ram C the abdominal protuberance on the ingot is forced in, so as to close the pipe and lift the segregate into it, as shown at III.

(Trans. Am. Inst. of Mining Engrs, Vol. XXXVIII.)

hastened on the right-hand side and retarded on the left-hand side, which resulted in shifting the pipe distinctly to the left of the axis.

Several methods have been used to produce sound ingots, as stirring the steel in the casting ladle to allow the gases to escape; casting on a turntable that is made to revolve and the metal run into a mold at its center; bottom casting, with a closed top instead of the ordinary open-topped molds; and casting under pressure.

There are different methods of exerting the pressure on the fluid metal in the mold. At the Krupp mills, fluid compression was tried by applying the pressure exerted by carbonic anhydride in its fluid state, the ingot mold being capped after the ingot was cast and connected to a reservoir containing the carbonic anhydride.

At the Edgar Thompson works the same principle was applied, using steam under a pressure of about 200 pounds per square inch. Under this steam pressure the ingot of 5 or 6 inches diameter shortened in length from 1½ to 2 inches.

Illingworth's process (Fig. 294) consists of casting in vertical molds, split lengthwise. The two halves are separated during the casting, but when the crust is formed they are brought together by a ram.

Williams' system (Fig. 295) employs the split mold, and the two sides are pressed together with a liner between.

The Whitworth process (Fig. 296) consists of using a steel mold which is placed in a hydraulic press and the fluid steel subjected to a pressure of about 6 or 7 tons per square inch of horizontal section. Under this pressure the ingot shortens about 1½ inches per foot of its length. This process produces an ingot of uniform quality throughout and in a great measure overcomes the difficulty experienced from the formation of blowholes and piping.

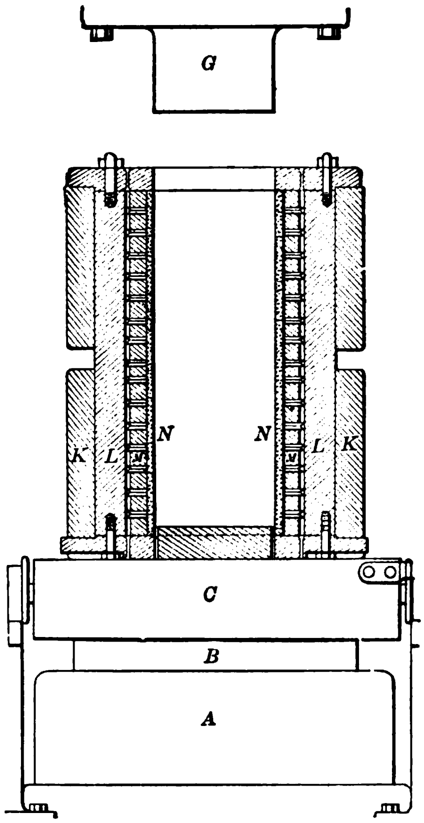


FIG. 296. — Whitworth's Hydraulic Press for the Compression of Steel Ingots while Solidifying.

A, main compression-cylinder. *B*, its plunger. *C*, the carriage on which the mold or flask sits. *G*, boss against which the steel in the mold is forced. *KK*, steel jackets for the mold. *LL*, the mold proper. *MM*, perforated cast-iron lagging. *NN*, inner sand lining.

(Trans. Am. Inst. of Mining Engrs., Vol. XXXVIII.)

The Harmet process (Fig. 297) consists in using a tapering mold and compressing the fluid by means of a hydraulic ram acting on the open end of the mold. The effect of the tapering mold is to exert a lateral pressure which tends to close up any axial pipes. The French Government require 28 per cent crop in uncompressed ingots and only 5 per cent in compressed ingots made at the St. Etienne works by the Harmet process.

The test pieces cut from the compressed ingots show, without forging or rolling, as good results under tensile and impact tests as test pieces cut from ingots of the same composition which had been forged with a reduction of two times in the cross-sectional area. There is a very marked diminution of segregation, the chemical analyses at the top and bottom of the ingot being substantially the same. The compressed ingot has a grain of a visibly finer structure and the large cleavages often found in sections cut from uncompressed ingots are not found. The metal is sound and thoroughly homogeneous.

Fluid compression of the steel in the ingot, when in proper hands, according to our present evidence, prevents pipes, blowholes, and cracks almost completely, and, to a limited extent, segregation. While its introduction would certainly lead to complication at the mills, the benefits to be derived warrant a trial of this method.

FIG. 297.—Harmet's Liquid Compression by Wire Drawing.

The ingot, AA, is cast in a strong conical mold, 27, reinforced with hoops, 28. Strong pressure at the base of the ingot, 26, forces it lengthwise of the mold, thus compressing it radially.

(Trans. Am. Inst. of Mining Engrs., Vol. XXXVIII.)

As has been seen the greatest defects are found in the upper part of the ingot, and to obtain a sound ingot it was generally specified that a certain discard or crop should be made from the top of the ingot, which it was supposed would contain all, or nearly all, of the imperfect metal.

To get definite knowledge on this point Dr. P. H. Dudley experimented by lettering the rails formed from different parts of the ingot. The rails were lettered "A" for the top rail, "B" for the second rail, and "C" for the third, or rail from the bottom part of the ingot. These letters could be found in the tracks, and, as was to be expected, the "A" rails have a larger percentage of impurities than the "B" or "C" rails. They wear faster, developing more surface defects, and at several points upon the road (the New York Central), under heavy traffic, after 10 or 12 years' service, have become practically worn out for main-line traffic, while the "B" or "C" rails are still good.

The Committee on Standard Rails of the American Railway Association reported at the meeting of the Association, April 22, 1908, on this subject, as follows:

All rails are to be branded with the name of the maker, the weight of the rail, and the month and year; and the number of the heat, and a letter indicating the portion of the ingot from which the rail was made, shall be plainly stamped on the web of each rail, where it will not be covered

by the splice bars. Rails to be lettered consecutively " A," " B," " C," etc., the rail from the top of the ingot being " A." In case of a top discard of 20 or more per cent, letter " A " will be omitted. All rails marked " A " shall be kept separate and be shipped in separate cars.

While railway engineers formerly specified a definite percentage of discard from the ingot, they now unanimously agree that the specifications should not state definitely how much should be sheared from the bloom, but that sufficient material should be discarded from the top of the ingots to insure sound rails. Records of rail failures which have been kept for a number of years disclose the incontrovertible fact that, where a 15 per cent discard might do for one ingot, 50 per cent would not be adequate for another.*

In its report the Committee of the American Railway Association says: With regard to the discard question, the Committee has always held that it would be preferable to test the finished product rather than specify as to the details of mill manufacture, and the Committee arranged for a trial lot of rails to be rolled from the ingot without any discard whatever, except such as was necessary to enable the bloom to enter the rolls, and after these rails had been cut into small pieces they were broken under the hammer and the fracture examined. This test proved to the satisfaction of the Committee that if "pipes" or other physical defects were present they could be detected by this means. The test also proved quite conclusively that it is possible so to conduct the process of manufacture that the "pipes" or other physical defects will be reduced to a minimum, and that these defects may not occur at all, even in rails rolled from the top portion of the ingot.

In order to avoid an unnecessary waste of good material, the Committee set about to devise means by which the rejection of defective material could be insured without requiring an arbitrary and definite percentage of discard in every case, and a committee of the Pennsylvania Railroad, pursuing the same line of investigation, adopted a tentative specification which provided for a physical test of this nature, and which further provided that when physical defects were discovered all top rails of the heat should be rejected. A trial lot of rails, of a section corresponding to " type B " (Plate VIII), was rolled under this specification as to discard, and the results convinced the committee that a development of this idea would prove the best solution of the discard problem.

Some of the advocates of a fixed and arbitrary discard have argued that the mere provision of a discard to insure the elimination of " piped " rails, or rails containing physical defects, was not sufficient, and urged the rejection of

* See Paper by W. C. Cushing before the Indiana Railroad Conmission, February 20, 1912.

a fixed percentage from the top of the ingot, because of the well-known fact that segregation occurs in the upper portion. This question of segregation was given careful consideration by the Committee, and while it is a fact that, due to the rearrangement of the constituent parts of the metal during the process of cooling and solidification in the ingot mold, any analysis of the metal in the finished rail will often show a wide departure from the analysis required by the specifications, it is also true that an analysis of the metal taken from the different parts of the finished rail will frequently show similar wide variation. This discrepancy is due to the fact that the test ingot referred to in the specifications, and upon which the chemistry specification is based, is taken from the ladle before the metal is poured into the ingot mold, and, consequently, before the segregation takes place.

It has been assumed that, because of this variation from the standard composition of the metal in the finished rail, the rejection of all segregated metal would be warranted. But, on this assumption, it would be necessary to discard more than a third of the upper part of the ingot to be on the safe side, as the segregation frequently extends that far; and, while our knowledge of the subject is not so complete as we could wish it to be, we have a great deal of evidence that rails of good physical condition can be made from the upper portion of the ingot. Furthermore, the analyses of a large number of rails, taken after years of service, indicate that these wide variations in chemical composition may occur without apparently affecting the safety or wearing quality of the rail; and, since it is impossible to check the analyses of the finished rail with that of the test ingot, the question arises as to what limits should be placed on the variation which will be permissible. None of the experts consulted are ready to say what this limit should be, and all admit that no facts are available as the results of actual experience which would warrant the adoption of any fixed limit to govern the rejection of material.

The provision in the new specifications for stamping the rails to show their position in the ingot will enable us to obtain more definite information on this point in the future.

BIBLIOGRAPHY

Beikirch, F. O. — Verfahren zur verhütung der lunkerbildung in schweren rohstahlblöcken, 1800 w. Ill. 1905. (In Stahl und Eisen, Vol. 25, Part 2, p. 865.)

Describes use of sinking-head, afterwards cut off. Piped portion is thus removed.

Daelen, R. M. — Die verfahren zur verhütung der lunkerbildung in stahlblöcken. 1800 w. Ill. 1905. (In Stahl und Eisen, Vol. 25, Part. 2, p. 923.)

The same. (In Zeitschrift des Vereines Deutscher Ingenieure, Vol. 49, Part 2, p. 1398.)

Describes fluid compression methods, methods of heating moulds and continuous process, proposed by writer.

Dormus, A. V. — Die blasen- und lungerbildung des flusseisens. 1000 w. Ill. 1902. (In Zeitschrift des Österreichischen Ingenieure- und Architekten-Vereines, Vol. 54, Part 1, p. 279.)

The same, translated. (In Sibley Journal of Engineering, Vol. 17, p. 128.)
Describes formation of blow-holes and pipes in steel and gives mechanical and chemical means for prevention.

DUDLEY, P. H. — Dark carbon streaks in segregated metal in split heads of rails. 2000 w. Ill. 1909. (In Proceedings of the American Society for Testing Materials, Vol. 9, p. 98.)
The same. (In Railway and Engineering Review, Vol. 49, p. 626.)

HÉROULT, P. L. T. — Presence and influences of gases in steel. 800 w. 1910. (In Transactions of the American Electrochemical Society, Vo. 17, p. 135.)
Concludes that blow holes are the result of disengagement of carbon monoxide in steel.

HOWE, HENRY M. — Does the removal of sulphur and phosphorus lessen the segregation of carbon? 2500 w. 1907. (In Proceedings of the American Society for Testing Materials, Vol. 7, p. 75.)
Results from examination of many cases indicate that removal of sulphur and phosphorus does not lessen segregation of carbon.

HOWE, HENRY M. — Further study of segregation in ingots. 5000 w. Ill. 1907. (In Engineering and Mining Journal, Vol. 84, p. 1011.)
Suggests that quiet, resulting from increased ingot-size and slow cooling, may explain why these conditions do not always favor segregation.

HOWE, HENRY M. — Influence of ingot-size on the degree of segregation in steel ingots. 800 w. Ill. 1909. (In Transactions of the American Institute of Mining Engineers, Vol. 40, p. 644.)

HOWE, HENRY M. — Influence of top-lag on the depth of the pipe in steel ingots. 1000 w. 1909. (In Transactions of the American Institute of Mining Engineers, Vol. 40, p. 804.)

HOWE, HENRY M. — Piping and segregation in steel ingots. 106 p. Ill. 1906. (In Transactions of the American Institute of Mining Engineers, Vol. 38, p. 3.)
Discussion, Vol. 39, p. 818. 33 p.
Considers causes and prevention of piping and of segregation and precautions to be taken regarding these in specifications.

HOWE, HENRY M. — Segregation in steel ingots. 1000 w. 1908. (In School of Mines Quarterly, Vol. 29, p. 238.)
Summarizes results of author's investigations.

HOWE, HENRY M., and STOUGHTON, BRADLEY. — Influence of the conditions of casting on piping and segregation, as shown by means of wax ingots. 3000 w. Ill. 1907. (In Transactions of the American Institute of Mining Engineers, Vol. 38, p. 109.)
Verifies by experiments views expressed by Howe in earlier paper.

HUSTON, CHARLES L. — Experiments on the segregation of steel ingots in its relation to plate specifications. 3000 w. Ill. 1906. (In Proceedings of American Society for Testing Materials, Vol. 6, p. 182.)
Illustrates and explains cases of segregation.

JOB, ROBERT. — Investigation of defective open-hearth steel rails. 1500 w. Ill. 1909. (In Proceedings of the American Society for Testing Materials, Vol. 9, p. 90.)
Discussion, p. 106.
The same. (In Railway Age Gazette, Vol. 48, p. 523.)
Shows failures to be due to unsoundness of metal.

KNIGHT, S. S. — Observations on segregation phenomena as applied to cast steels. 3000 w. Ill. 1910. (In Iron Trade Review, Vol. 46, p. 475.)
Paper before Philadelphia Foundrymen's Association.
Illustrates examples of segregation and emphasizes need of further investigations.

LILIENBERG, N — Piping in steel ingots. 2000 w Ill. 1906. (In Transactions of the American Institute of Mining Engineers, Vol. 37, p. 238.)
Considers methods for prevention of piping, with special attention to Illingworth's side-compression method.

MATHESIUS, W. — Herstellung von poren- und lunkerfreiem grauguss, stahlguss und schmiedestücken durch anwendung von thermit 2500 w. Ill. 1903. (In Stahl und Eisen, Vol. 23, Part 2, p. 925.)

RIEMER, JULIUS. — Ein neues verfahren zum verdichten von stahlblöcken in flüssigem zustande. 2000 w. Ill. 1903. (In Stahl und Eisen, Vol. 23, Part 2, p. 1196.)
The same, translated. (In Iron and Coal Trades Review, Vol. 67, p. 1776.)
New method consists in pressing of ingot from below, allowing gases to escape at the top.

SAUVEUR, ALBERT, and WHITING, JASPAR. — Casting of pipeless ingots by the Sauveur overflow method. 1500 w. Ill. 1903. (In Proceedings of the American Society for Testing Materials, Vol. 3, p. 129.)
Segregation in soft steel ingots; its effect on rolled material as shown in tensile and shock tests. 2500 w. Ill. 1910. (In Iron Age, Vol. 86, p. 730.)
Gives results and conclusions reached by Wüst and Felser in paper in "Metallurgie." Shows segregation to have greatest influence in shock tests, as segregated material is very brittle.

SPRINGER, J. F. — Piping in steel ingots; methods for its reduction and elimination. 4000 w. Ill. 1909. (In Cassier's Magazine, Vol. 35, p. 426.)

SPRINGER, J. F. — Thermal treatment of steel ingots. 1200 w. Ill. 1910. (In Scientific American, Vol. 116, pp. 262, 269.)
Describes piping and segregation phenomena and briefly reviews methods for prevention.

STEAD, J. E. — Crystallization and segregation of steel ingots. 53 p. Ill. 1906. (In Proceedings of the Cleveland Institution of Engineers, 1905–06, p. 163.)
Review of work done on the subject, with conclusions.

TALBOT, BENJAMIN.—Segregation in steel ingots. 44 p. Ill. 1905. (In Journal of the Iron and Steel Institute, Vol. 68, p. 204.)
Includes extensive tabulated data on the effect of additions of small amounts of aluminum to the ingot.
WAHLBERG, AXEL.—Influence of chemical composition on soundness of steel ingots. 38 p. Ill. 1902. (In Journal of the Iron and Steel Institute, Vol. 61, p. 333.)
WEDDING, H.—Untersuchung über den ursprung eines blasenraumes in einen flusseisenblocke. 2000 w. Ill. 1905. (In Stahl und Eisen, Vol. 25, Part 2, p. 832.)
Considers probable origin of a blow-hole in a 2-ton ingot. Faulty shape of mould considered to be explanation.
Weitere entwicklung des Riemerschen verfahrens zur herstellung dichter stahlblöcke. 1000 w. Ill. 1904. (In Stahl und Eisen, Vol. 24, Part 1, p. 392.)
Illustrates great reduction in piping from use of new method of Riemer.
WICKHORST, M. H.—Low-carbon streaks in open-hearth rails. 1200 w. Ill. 1910. (In Proceedings of the American Society for Testing Materials, Vol. 10, p. 212)
Studies rails that developed a peculiar kind of failure, shown to be due to streaks of metal low in carbon.
WICKHORST, M. H.—Segregation and other rail properties as influenced by size of ingot 97 p. Ill. 1911. (In Proceedings of the American Railway Engineering Association, Vol. 13, p. 655.)

33. INFLUENCE OF MECHANICAL WORK

The principal points in connection with the rolling are given below:

1. Resistance to wear is a function of fineness of grain.

2. Fineness of grain is principally a result of mechanical treatment at proper temperature.*

3. Work done on steel above 950°–1050° C. (1742° F.–1922° F.) has less effect on changing the size of grain from the normal crystallization of the ingot than when the rolling is done at a lower temperature.

Fig. 298 shows the steel entering the rolls. Figs. 299, 300, 301, and 302 illustrate views taken by Mr. Howard and show the gradual reduction of the bloom to the finished rail as it passes through the successive rolls.

In 1909 a further investigation was made of the steel at different stages of the rolling by James E. Howard at the Watertown Arsenal.† In these tests, beginning with the ingot, the structural state of the metal was examined by taking cross sections and longitudinal sections. This method was carried through the various successive derivative shapes, and the results obtained are shown in the large number of illustrations which form the body of the report.

The greater part of the work was devoted to Bessemer rail steel, five acid Bessemer heats being made for this series of tests, each heat furnishing six ingots about 19½ by 20½ inches at the bottom and about 5 feet high.

One of the most important results of the tests was to throw light on the question of the amount of work or reduction necessary in rolling to develop the full physical qualities of the steel. Mr. Wickhorst draws the following

* This should not be interpreted as meaning that resistance to wear is not a function of the chemical composition.

† Tests of Metals, etc., 1909, Vol. 1 and Vol. 2, Government Printing Office, Washington.

FIG. 298. — Steel Entering the Rolls. (Am. Tech. Soc.)

conclusion from the tensile tests made of specimens taken at various stages from the ingot to the finished rail.

FIG. 299. — Cross Section of 8 by 8 in. Rail Bloom Rolled from an Ingot 20 ins. Square. (Am. Ry. Eng. Assn. — Howard.)

The results indicate that the metal in the walls of the ingot takes comparatively little work or reduction to impart to it what may be called its full

FIG. 300. — Rail from an Early Pass in Roughing Rolls, Rolled from Bloom Shown in Fig. 299. (Am. Ry. Eng. Assn. — Howard.)

physical properties of tensile strength and ductility. These are reached in the bloom, except at the top end. The axial metal at the bottom of the ingot also

FIG. 301. — Same Rail as Shown in Fig. 300 after Further Reduction.
(Am. Ry. Eng. Assn. — Howard.)

soon reaches its full physical properties, but in the upper half of the ingot it must be carried well toward the finished rail before these properties are fully developed.

FIG. 302. — Finished Rail from Same Ingot as Bloom and Pieces from Roughing Rolls.
(Am. Ry. Eng. Assn. — Howard.)

Where the metal is of fairly even composition and free from sponginess, it reaches its full physical qualities of tensile strength and ductility at about ten reductions or a reduction to one-tenth of the original cross section of the ingot, but the interior portion of the upper part of the ingot requires twenty-five or more reductions to have its full physical qualities developed, that is, the cross-sectional area must be reduced below one twenty-fifth of its original amount.

Table XCII gives the result of tests by Sauveur on the relation between the size of the grain and the physical properties of the same piece of steel.*

TABLE XCII. — RELATION BETWEEN SIZE OF GRAIN AND PHYSICAL PROPERTIES OF STEEL

(Sauveur)

Size of Grain.		Tensile Strength.		Elongation Per cent of Length.	Reduction of Area, Per cent.
In 0.0001 Square Millimeter.	Number per Square Inch, Approximately.	Kilograms per Square Millimeter.	Pounds per Square Inch.		
148	44,000	69.6	99,000	15.0	20
118	54,000	70.3	100,000	19.0	22
62	104,000	77.7	110,000	22.5	35

1 kilogram = 2.2046 pounds. 1 square millimeter = .00155 square inch.

Mr. Robert Job, chemist of the Philadelphia & Reading Railroad, states that "in a lot of over 75,000 tons of rail observed during a period of five years, we have 15 times as many fractures in service from rails of coarse grain, or 19,600 cells per square inch, as from rails of medium fine structure, 48,400 cells per square inch, and there is also a marked difference in capacity for wear in favor of the finer structure rail. Out of several thousand tons of rail now (1905) in our tracks, made with a clause in the specifications requiring more than 40,000 cells per square inch, only one rail has fractured in service, and that owing to pipes in the steel in process of manufacture."

Dr. P. H. Dudley states that rails of 100-pound section with 48,000 to 70,000 cells per square inch after having sustained 250,000,000 tons in the track were still in good condition.

The rolling tends to break down the grain and give a finer structure, but immediately after the work stops the grain commences to grow again, consequently the lower the finishing temperature the smaller the grain size. If the steel is worked below the critical point, strains are developed which injure the metal and may rupture it. Work at too low a temperature distorts the grain or flattens and elongates the crystals in the direction of the rolling.

* N. Ljamin, Chem. Zeit, 1899, Baumaterialien, 1899, finds the tenacity in different steels varies directly as the size of the pearlite grains, at the same finishing temperature.

To thoroughly understand the effect of the rolling, it is necessary to study the structural changes that take place in the cooling metal.*

Let us first consider the cooling curve of a copper bar, shown in Fig. 303. We find here no evidence of any sudden change in the nature of the cooling copper.

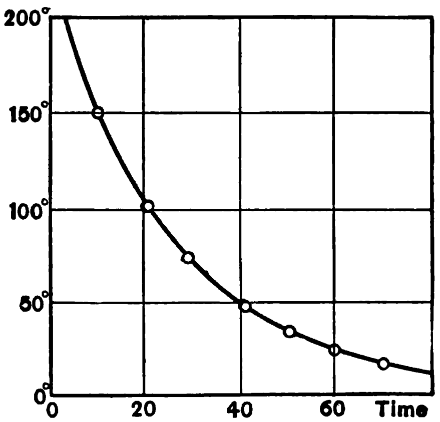


FIG. 303. — Cooling Curve of Solid Copper. (J. W. Mellor.)

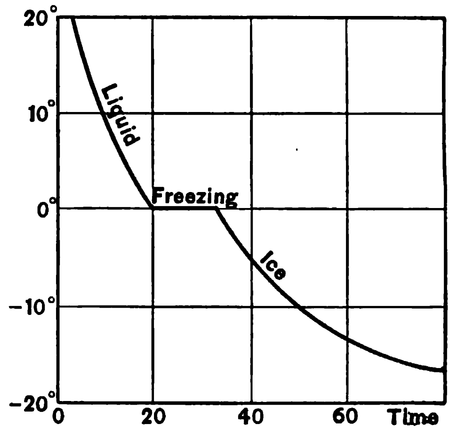


FIG. 304. — Cooling Curve of Water. (J. W. Mellor.)

If, however, a curve is drawn for water cooling down from 20° to −20° C., we get a terrace in the cooling curve, as shown in Fig. 304. This tells us that some change has taken place in the nature of the substance at 0°. We see at

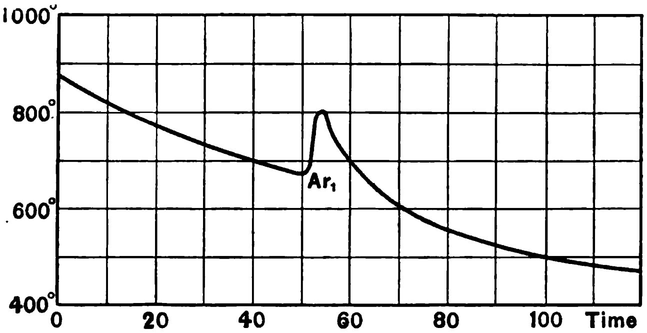


FIG. 305. — Recalescence. (J. W. Mellor.)

once that this change corresponds with the passage of water from the liquid to the solid state.

When a steel bar is cooling, an evolution of heat occurs at about 690° C. The amount of heat evolved is so great that the metal visibly brightens in color. The phenomenon is called "recalescence." The cooling curve is shown in Fig. 305.

* See The Crystallization of Iron and Steel, J. W. Mellor, 1905.

The cooling curve of iron from the molten condition is shown in Fig. 306. The iron was practically pure, containing only .01 per cent of carbon.

Osmond maintains that the existence of the transition points, Ar_3 and Ar_2, in the cooling curve of the solidified metal points to the existence of three allotropic modifications of solid iron. Each critical point is found to be associated with a change in the mechanical properties, the microscopic appearance, and the specific gravity of the metal.

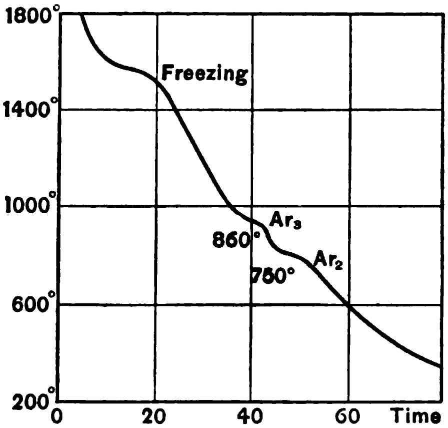


FIG. 306. — Cooling Curve of Iron. (J. W Mellor.)

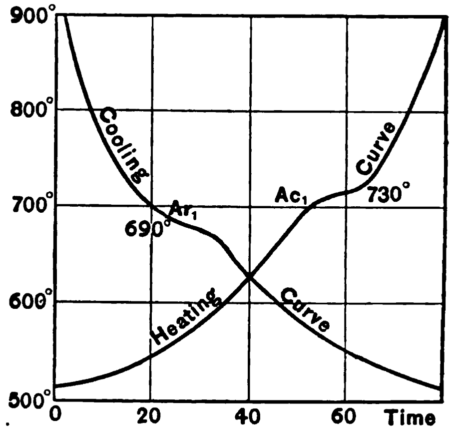


FIG. 307. — Cooling and Heating Curves of Steel. (J. W. Mellor.)

The changes which occur during the cooling of a substance are reversed when the substance is heated. The cooling curve of steel, with 1.2 per cent of carbon, shown in Fig. 307, is reversed on heating, as shown by the heating curve in the same diagram.

The critical points on the heating curve of mild steel are generally a few degrees higher than the corresponding points on the cooling curve.

Let us now consider what takes place when steel containing 0.6 per cent carbon cools from 900° C. The cooling curve shows nothing very remarkable until a temperature of about 720° C. is attained. Here the critical points Ar_3 and Ar_2 of pure iron coalesce into one. At this point pure iron, or ferrite, separates from the solid solution. The separation of ferrite goes on along the curve AP (Fig. 308) until the temperature reaches about 690° C., when another recalescence point occurs (Ar_1). No other essential change, as far as we are concerned, occurs as the system cools down to the normal temperature of the atmosphere.

Fig. 308 is derived from Roozeboom's diagram,* the carbon-iron diagram,

* H. W. B. Roozeboom, Zeit. Phys. Chem., 34.437, 1900; improved in Zeit. Elektrochem., 10.489, 1904; Metallographist, 3.293, 1900; H. le Chatelier, ibid., 3.290, 1900; 4.161, 1901; F. Osmond, 4.150, 1901; H. Jüptner von Jonstorff, ibid., 5.210, 1902.

given by Howe,* based upon later researches, shows the temperatures somewhat higher than those of the figure.

When the temperature is above the line APB the iron is in a form known as "austenite." Whatever carbon is present is dissolved in this austenite, which is what is called a "solid solution" as distinguished from a mechanical mixture or conglomerate, just as salt and water, when brought in contact, merge in each other and pass from the condition of a mixture or conglomerate to that of a single substance.

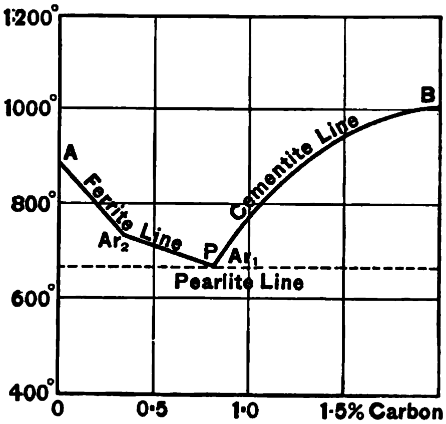


FIG. 308. — Cooling of "Solid Steel." (J. W. Mellor.)

As the iron with 0.6 per cent carbon cools and the line AP is reached the austenite begins expelling from itself part of its iron in the form of ferrite. As the ferrite thus expelled is nearly or quite free from carbon, the remaining austenite becomes relatively richer in carbon, until, when the temperature reaches Ar_1, it contains 0.9 per cent carbon which is the carbon content of pearlite. On cooling past this point all the austenite changes into pearlite, with no change in the ferrite which it has generated in the passage along the line AP, so that the steel now consists of a conglomerate of ferrite and pearlite. This conversion of the austenite into pearlite is accompanied by a considerable evolution of heat, and is shown by the recalescence curve of Fig. 305.

Steels containing just 0.90 per cent carbon, and hence consisting of pearlite alone, are called "eutectoid" steels. Those containing less than this are called "hypo-eutectoid," and those more than this, "hyper-eutectoid" steels.

As previously stated, work below the Ar_1 point distorts the grain or flattens and elongates the crystals in the direction of the rolling.

The result of work above the Ar_1 point is to retard the growth of the grains. Howe† explains the relation between the temperature of the hot work and the size of the grain as follows:

The mechanical distortion in rolling elongates these grains in the direction of rolling and shortens them in the plane of the pressure; this appears to throw the metal crystallographically into unstable equilibrium, with the result that

* Life History of Network and Ferrite Grains in Carbon Steel, H. M. Howe. Proceedings, American Society for Testing Materials, Vol. XI, 1911, p. 266.

† H. M. Howe, Iron, Steel, and Other Alloys, 1903, p. 262.

the old grains thus distorted break up, and that the metal rearranges itself into new and equiaxed grains.

But these new grains assume a size normal, not to the temperature at which the old ones had formed, but rather to the temperature now existing; during the rolling the temperature is constantly falling; each pass through the rolls tends more or less fully to break up the preëxisting grain, and to substitute for it a new grain of a size more nearly normal to the now lower temperature. To speak more accurately, the new grain size approaches that normal for the existing temperature; but the result is much the same. For if each of a succession of passes through the rolls breaks up the existing grain, and substitutes for it a new one, then each new grain will be smaller than the preceding, because the normal towards which it tends is smaller than the normal towards which its predecessor tended at the higher temperature then existing.

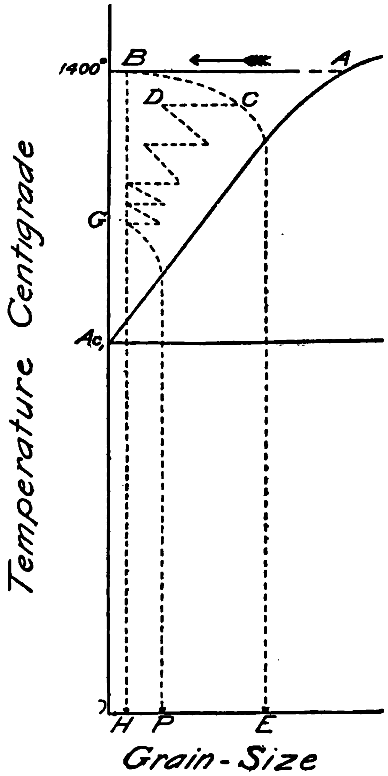


FIG. 309. — The Influence of the Finishing Temperature on the Size of Grain. (Howe.)

Fig. 309 attempts to express this condition of affairs graphically. Here ordinates represent temperature and abscissæ coarseness of grain. The line Ac_1A may be taken as representing roughly the normal size of grain, D^n, which steel of given composition tends to assume with varying temperature, or the line of normal coarseness of grain. If the grain is smaller than the normal for existing temperature, it always tends to grow and to approach that normal. If it is coarser than that normal, it does not tend to shrink back towards the normal, except when the temperature is rising past Ac_3.

Let us suppose that we cease rolling a piece of steel while its temperature is at *B*, the mechanical work of the rolls having broken the grain down. During subsequent cooling the grain will grow, somewhat as sketched in the line *BCE*. If, however, we resume rolling when the grain has reached *C*, we will break down the grain, and drive it back, say to *D*. And so, keeping on, between passes the grain grows and the temperature simultaneously falls, while at each pass the squeeze which we give the metal breaks up the grain, and the curve of grain and temperature follows the zigzag line *BCDG*.

If we cease rolling when the temperature has fallen to G, then the grain will grow as the metal cools, till the line of the actual size of grain intersects that of the normal size, the line Ac_1A; with further cooling no further growth ensues, and the final size of grain is OP. If we had quenched the metal while at G, the final size of grain would have been OH. If we had ceased rolling when the temperature was at B, the final size of grain in the cooled steel would have been OE.

Generally speaking, the grain size will be the coarser the higher the finishing temperature. Fig. 310 illustrates this principle. This shows the microstructure of two like bars of the same steel, of which each had first been heated

Cooled to 963° C. Cooled to 837° C.

FIG. 310. — Influence of Finishing Temperature on the Size of the Grain of Steel of 0.50 per cent Carbon (Howe.)

to 1394° C., then cooled slowly to the temperature indicated in the figure, then rolled, and then cooled slowly, so that these temperatures are the "finishing temperatures." Note how much coarser the meshes are in A, finished at 963° C., than in B, finished at 837°.

Professor Sauveur's micrographs of rail structure show that in the section of a given rail, the network, or size of the walled cells, is the coarser the higher the temperature at which the rolling is finished.*

According to Howe, when a piece like a rail, which is highly heated, is rolled with such heavy reduction as to distort the austenite grains greatly, the distorted and hence unstable grains immediately shatter, and their remains immediately begin growing again by coalescence. This is repeated as often as the piece is greatly reduced by the rolling. Each of the grains of austenite, formed by coalescence after the last of these reductions, in cooling down to the Ar_1 point, gives birth to a walled cell by ejecting to its outside the ferrite which it generates. Hence it is the size which these austenite grains reach after this last

* Trans. American Institute of Mining Engineers, Vol. XXII, 1893, pp. 546–557, and especially Plates IV and V.

effective reduction that determines the network size of the cold steel, and as regards the opportunity for network growth, the finishing temperature is the equivalent of the highest temperature reached by objects not rolled.

This well-marked network common to rail steels is probably due to their large manganese content, as otherwise, on account of their slow cooling, the ferrite would coalesce and break up the network.*

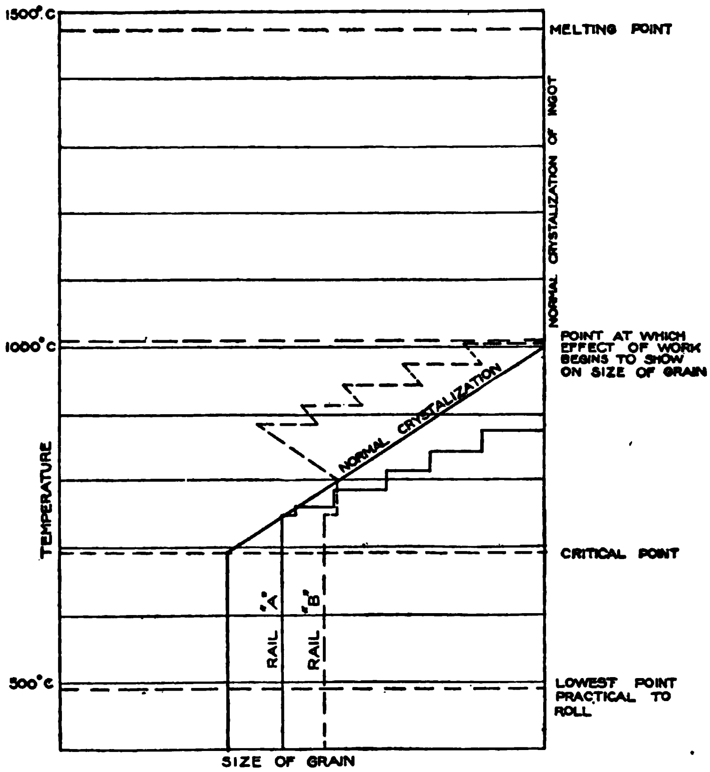


FIG. 311. — Diagram of Results of Experiments on Rolling at Different Temperatures.

This principle of governing the grain size by means of the finishing temperature is of very great importance. In general, we should be inclined by considerations of economy of power to roll steel as hot as we dare, because the hotter it is the softer it is, and the less power is consumed in rolling. But this would naturally lead to a high finishing temperature, and thus to coarseness of grain and brittleness. Hence a high temperature is desirable as regards power consumption, but undesirable as regards the quality of the steel.

† Fig. 311 shows graphically the results of experiments made at the Spar-

* For illustration of this cellular structure in rails see Job, The Metallographist, Vol. 5, 1902, pp. 177–191; P. H. Dudley, ibid., Vol. 6, 1903, p. 111.

† The Manufacture and Properties of Iron and Steel, H. H. Campbell, 1904, p. 410.

rows Point plant of the Maryland Steel Company. As in Fig. 309 ordinates represent temperature and abscissæ coarseness of grain, the grain growing coarser from left to right. An ingot was rolled into blooms and two adjacent blooms, "A" and "B," were rolled into rails without further heating, the first, "A," being held before rolling in order to allow it to cool so that all work should be done at as low a temperature as possible, without, of course, reaching the lower critical point, while the second, "B," was rolled as quickly as possible through all the passes, except the last, but was then held at the finishing pass $1\frac{3}{4}$ minutes; the result being that both pieces went through the finishing pass at the same temperature, which was about 750° C. (1382° F.).

FIG. 312. — Rail "B" Near Surface, 46 Dia. — Campbell.

FIG. 313. — Rail "A" Near Surface, 46 Dia. — Campbell.

Fig. 312 shows "B" rail near the surface.

Fig. 313 shows "A" rail near the surface.

FIG. 314. — Rail "B" Center of Head, 46 Dia. — Campbell.

FIG. 315. — Rail "A" Center of Head, 46 Dia. — Campbell.

Fig. 314 is from the center of the head of "B" rail.

Fig. 315 is from the center of the head of "A" rail.

While Figs. 312 and 313 appear similar, Figs. 314 and 315 show the real difference between the two rollings. The last pass does very little work; there-

fore, holding the rail before the last pass does little good, except on the outer surface of the rail, and a low shrinkage or finishing temperature does not necessarily mean that the rail will have a good grain throughout.

Fig. 316. — Top View at Top of Head, 70 lb. Rail, 50 Dia. (Am. Ry. Eng. Assn.)

Fig. 317. — Top View at Center of Head, 70-lb. Rail, 50 Dia. (Am. Ry. Eng. Assn.)

Fig. 318. — Side View at Top of Head, 70-lb. Rail, 50 Dia. (Am. Ry. Eng Assn.)

Fig. 319. — Side View at Center of Head, 70-lb. Rail, 50 Dia. (Am. Ry Eng. Assn.)

Figs. 316 to 321 presented by Wickhorst* illustrate the different grain found in the top and center of a new 70-pound Bessemer rail. A section about ¼ inch

* Flow of Rail Head under Wheel Loads, M. W. Wickhorst, Am. Ry. Eng. & M. of W. Assn., Vol. 12, Part 2, 1911, p. 535.

thick was taken from the rail and two pieces cut from it for microscopic test, as shown in Fig. 322. These pieces were polished on three sides, etched with

FIG. 320.—Transverse View at Top of Head, 70-lb. Rail, 50 Dia. (Am. Ry. Eng. Assn.)

FIG. 321. — Transverse View at Center of Head, 70-lb. Rail, 50 Dia. (Am. Ry. Eng. Assn.)

10 per cent solution of nitric acid in alcohol, and microphotographs made, magnified 50 diameters. Thus, horizontal, vertical transverse, and vertical longitudinal sections were obtained at the top and at the center of the head.

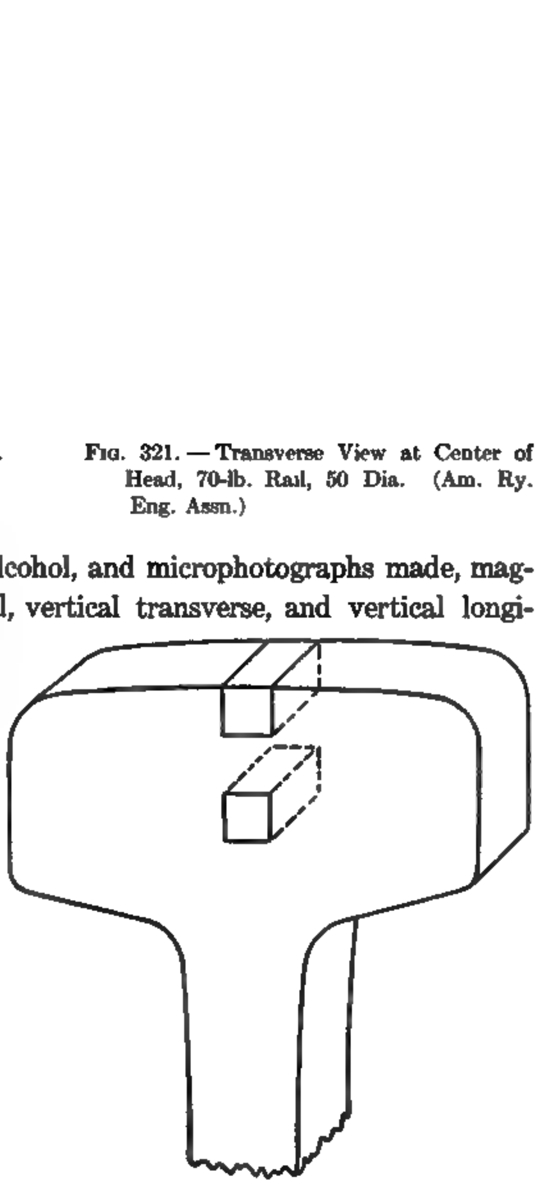


FIG. 322. — Pieces for Microscopic Views shown in Figs. 316 to 321.

There will always be some difference between the structure of the center of the head and the portion near the surface, but when the rail is rolled at a proper temperature during the passes, when considerable work is put upon the piece, this difference will not be serious.

The effect of finishing temperature is not fully agreed upon, and many rolling-mill men feel that the properties of the steel depend quite as much on the amount of reduction in the rolls as upon the finishing temperature.

* To try to arrive at some conclusion in this matter, a number of temperature readings were taken with both the Féry and Wanner pyrometers and checked against a thermo-couple at one or two large plants. For steel rails the finishing temperatures as indicated by the optical pyrometers averaged 1050 to 1100° C.;† for structural steel, 950 to 1000° C. And yet such material is not coarse-grained. (Reheating to such a temperature would give rail steel a very coarse grain.) A difference of over 100° C. in finishing temperature could not be detected in the size of grain, but a difference in section could very soon be noticed. Similar results can be reached experimentally by rolling out small sections at different temperatures. A section heated to 1300° C. and rolled out with 30 per cent reduction showed about the same sized grain as one heated to 1300° C., cooled to 900°, and rolled out, the finishing temperature being about 700° C.

The question of rolling at a low temperature is one that has occupied the minds of engineers for a long time, and the fact that at present no solution has been made which is satisfactory to both the manufacturer and the consumer is evidence that it is not easily put aside.

In rolling early rails it was recognized that mechanical defects would be developed to a greater or less extent by the rolling process, and therefore the bloom, about 7 inches square, was conveyed from the blooming rolls to a steam hammer by which all visible cracks or defects were chipped out, care being taken to cut to the bottom of the imperfection, and not leave any pronounced shoulders at the edges of the resulting depressions; and until the adoption of automatically operated tables attached to the rail rolls, if the partially formed rails still showed defects, the operation of rolling was halted, while such places were chipped out by hand. These were usual practices, and were not abandoned because of their results being unsatisfactory, but on account of the time consumed and the expense incurred.

In the formation of the grooves in the rolls much damage can be and often is done to the steel. With the object of increasing the product of a given mill, the ingot is rolled off at one heat, with heavy reductions in each pass so as to reduce the number of passes and consequently the time taken in rolling.

It is interesting to turn to the following review of the English practice by Mr. Talbot:‡ "Our practice is to take large ingots and have a furnace between

* Some Practical Applications of Metallography, Campbell. Proceedings American Society for Testing Materials, Vol. VIII, 1908, p. 353.

† These temperatures are from 100 to 200 degrees higher than the usual practice.

‡ On Rail Steel as Manufactured by the Continuous Open-hearth Process, Talbot. Proceedings American Society for Testing Materials, Vol. VII, 1907.

the cogging and finishing mills,* which has the effect of acting as an equalizer so that the blooms are delivered to the finishing mill at an even temperature, making the bar more easily shaped, and the flange of the rail is sent out of the finishing groove at a temperature nearer to that of the head than has hitherto been possible. This, no doubt lessens the strains set up in cooling on the hot banks. Our practice is to increase the number of passes, decrease the amount of reduction per pass, and get the product by increased speed of the rolls and not by digging into and tearing the metal, as is done in the case where too few passes and heavy drafts are adopted.

"With regard to rolling temperature, we may say we roll a 100-pound rail in lengths which give, after crops are cut off, three lengths of 10 meters. The first length is cut within 15 to 20 seconds after leaving the finishing groove of the mill, and on this we allow $7\frac{3}{8}$ inches shrinkage. The next length is cut within 35 to 50 seconds from leaving groove, and here $7\frac{1}{4}$ inches is allowed. The third is within 60 to 80 seconds, and 7 inches is allowed for shrinkage. Of course these allowances only apply to 100-pound rails; less allowance is made in lighter rails."

† At one of the large rail mills they formerly had a table on which the rails were held before they went through the finishing pass. The scheme of holding the rail before the finishing pass, where only a small amount of work is put upon the metal, as illustrated in Figs. 312, 313, 314, and 315, while giving a low finishing temperature, does not necessarily decrease the size of the grain.

Starting with such a scheme as a basis and designing the rolling mill to hold the pieces to allow them to cool before the passes where the most work is done, and also arranging for the sorting out of the blooms to equalize the finishing temperature, would give a better arrangement and would have merit if applied to mills where the rails are finished too hot as a direct result of producing large tonnage. However, even with the most careful manufacture, a certain amount of heat on the bloom is necessary in order to take the A. S. C. E. sections through with the flanges properly filled out, and it will not be possible to reduce this temperature without the danger of the breakage of rolls, improper filling out of the flange, and additional strains in the steel, which are necessarily detrimental, unless the design is changed to make all parts of the section more nearly in balance as to the temperature of finish.

An interesting experiment may be tried on a tee rail, which has been finished and straightened. Take 6 or 8 feet of rail and place it on a planing machine and cut the head off the web at the point where the web joins the head, and both

* This is customary at a number of rolling mills in America.

† Kennedy-Morrison Process. The Iron Age, December 20, 1900, pp. 16–18.

the head and bottom portion will spring out of a straight line, sometimes to a very marked extent, thus showing that great internal strains are there. This is a condition that cannot be avoided by the manufacturer without some help from the rail designer.

The better distribution of metal in the new American Railway Association sections gives a rail that can not only be rolled at a lower temperature, but which is much less liable to injury in the straightening press.

The rolling of these rails has developed some surprises. It was expected that the rails could be rolled at a lower temperature than the old sections, and that the shrinkage allowance could be reduced; but it was found that under the same conditions the new section would require a greater shrinkage allowance than the old. The rails were unquestionably rolled colder than the old section, with the exception of the thin flange, but it was this thin flange that determined the shrinkage of the old rails. In going through the cambering wheels the head was stretched, giving the hot head a greater length for shrinkage than the base. In the new section the temperature is nearly uniform and much colder than the head of the old rail was, but no part of the new rail is as cold as the thin base of the old rail; consequently a greater shrinkage allowance is required.

At Gary* the ingots are bloomed to 8 by 8 inches in 9 passes and finished in 9 passes, making a total of 18 passes from ingot to rail. The reduction of the rail is from 400 square inches at the bottom of the ingot to 10.1 square inches, or a reduction of 39 times. The areas of the various passes, as furnished by the Steel Company at Gary, of their section 10030, which is the A. R. A. type " B " 100-pound rail, are as follows:

Pass Number.	Area.	Pass Number.	Area.
	Square Inches.		Square Inches.
Ingot	400	10	43.2
1	376.6	11	32.9
2	282.4	12	25.2
3	214.9	13	21.5
4	164.8	14	17.8
5	130.3	15	16.4
6	107.9	16	13.2
7	88.9	17	10.7
8	70.8	18	10.1
9	58.9		

At the Maryland Steel Company† the blooms remain in the soaking pit about 1 hour and 25 minutes, and are rolled to $7\frac{3}{4}$ by $7\frac{3}{4}$-inch blooms in 13 passes, the top end of the ingot forward, and turned after each two passes. The blooms

* Report to Rail Committee, Proceedings Am. Ry. Eng. & M. of W. Assn., Vol. 12, Part 2, 1911, p. 430.

† Report to Rail Committee, Proceedings Am. Ry. Eng. Assn., Vol. 12, Part 2, 1911, p. 388.

are rolled directly into rails without reheating, in 11 passes, making a total of 24 passes from ingot to rail. The area of cross section in square inches in the various passes for the A. R. A. type "B" 90-pound rail, Maryland Steel Company, section No. 162, is about as follows:

TABLE XCIII.—REDUCTION OF AREA IN 90-LB. A. R. A. TYPE "B" RAILS ROLLED AT MARYLAND STEEL COMPANY

(A. R. E. Assn.)

Operation.	Number of Pass.	Area.	Operation.	Number of Pass.	Area.	Operation.	Number of Pass.	Area.
		Sq. In.			Sq. In.			Sq. In.
Ingot........	....	416	Blooming..	9	132	Roughing......	5	21.5
Blooming...	1	374	Blooming..	10	117	Roughing......	6	17.8
Blooming...	2	336	Blooming..	11	96	Intermediate...	7	16.0
Blooming...	3	300	Blooming..	12	74	Intermediate...	8	15.2
Blooming...	4	260	Blooming..	13	58	Intermediate...	9	12.3
Blooming...	5	234	Roughing..	1	46.2	Intermediate...	10	9.7
Blooming...	6	205	Roughing..	2	34.4	Finishing......	11	9.0
Blooming...	7	172	Roughing..	3	31.3			
Blooming...	8	150	Roughing..	4	23.1			

Table XCIV presents data on American rolling-mill practice. Fig. 323 shows the arrangement of the rail mill of the Algoma Steel Company's plant. This consists of one 32-inch rev. bloom mill, three Seimens heating furnaces for reheating the blooms, and one 23-inch three-high rail mill.

Plate XXX illustrates a reversing cogging mill and Plate XXXI and Fig. 324 three-high mills. The left hand illustration of Fig. 325 shows a set of rolls for use in a three-high mill, according to common English practice, in which the bottom and middle rolls are grooved to receive the rail, while the "closers" are on the middle and top rolls, and the guards to peel the bars out of the grooves rest by gravity on the bottom and middle rolls.

In the American three-high mill, shown on the same figure, the top and bottom rolls are grooved and the middle roll serves as the "closer" for each of the others, itself carrying no grooves at all; to enable the bars to be got out of the top groove, the upper guard must be placed on the upper side of the bar as it issues from the roll, and as it will not lie there by gravity, the guard has to be kept up to the roll by a counterweight or spring, and is known as a balanced guard.*

Fig. 326 shows the three-high rolls in the rail mill at Gary. †This mill is equipped with 12 sets or stands of roll trains, all operated at varying speeds by General Electric alternating-current motors, some of which are of the largest

* Steel, by Harbord and Hall, London, 1911, p. 625.

† Railroad Age Gazette, November 13, 1908, and The Iron Age, April 1, 1909.

TABLE XCIV. — DATA ON AMERICAN ROLLING-MILL PRACTICE

(Compiled by Committee on Rail, Am. Ry. Eng. Assn., 1909, and revised by the author 1912)

Rail Mill.	Location.	Blooming Mill. Section of Ingot.	Blooming Mill. Time in Rolling Ingots into Blooms.	Blooming Mill. Size of Bloom in Inches.	Number of Passes in Rail Train. Blooming.	Number of Passes in Rail Train. Roughing.	Number of Passes in Rail Train. Finishing.	Average Reduction per Pass, Ingots to Blooms.	Total Number of Passes of Rails.	Total Time of Rolling, Inclusive of Rests, from Time Ingot enters First Roll till it leaves the Finishing Roll.	Remarks.
			m. s.					Sq. In.		m. s.	
Algoma Steel Co.	Canadian Soo, Canada.	18½″×19½″	†2 30	†8″×8″	19	8	3	......	30	......	Blooms reheated.
†Bethlehem Steel Co.	Bethlehem, Pa.	19″×23″	1 20	8″×8″	15	10	1	24 8	26	6	Ingots are reheated after being taken from molds and are rolled direct without further reheating.
*Cambria Steel Co.	Johnstown, Pa.	20″×23″	2 45	8½″×10″	15	10	2	25.00 or 22 00	27	6 45	Ingots are reheated, rolled into blooms, again reheated and rolled into rails. No rest is given prior to finishing pass.
Carnegie Steel Co.	Braddock, Pa.	18″×20″	1 11	9½″×9½″	7	†12	1	38.53	†20	4 41	Ingots are reheated, rolled into blooms, again reheated and rolled into rails. Rails are given a rest immediately prior to finishing pass of from 1 min. to 1 min. 45 sec.
Carnegie Steel Co.	Braddock, Pa.	16½″×18½″	......	......	7	.	...	......	...	......	Old mill. Light rails. Rails not held between passes.
†Carnegie Steel Co.	Youngstown, Ohio.	19″×21″	50	8″×8″	9	10	1	35 50	20	4 50	
Colorado Fuel & Iron Co.	Pueblo, Colo.	20″×18″	......	......	17	7	5	......	29	......	
†Dominion Iron & Steel Co.	Sydney, Canada.	18″×21″	......	......	17	10	1	......	28	......	
*Illinois Steel Co.	S. Chicago, Ill.	†18″×19½″	†50	8″×8″	9	4	5	32 89	18	......	Rails held 30 to 60 seconds before finishing pass.
Indiana Steel Co.	Gary, Ind.	20″×24″	......	......	9	8	1	......	18	......	First rails shipped Feb. 26, 1909.
*Lackawanna Steel Co.	Buffalo, N. Y.	19″×19″	2 45	8″×8″	6	4	5	49 5	15	6 5	No rest prior to finishing pass.
*Maryland Steel Co.	Sparrows Pt., Md.	20″×21″	2 10	7¾″×7¾″	13	6	5	27 7	24	5 50	Ingots are reheated after being taken from molds and are rolled direct without further heating. No rest is given except that which occurs when bloom is being sheared.
*Pennsylvania Steel Co.	Steelton, Pa.	18½″×18½″	1 20	7½″×7½″	9	6	5	......	20	3	Same practice as at Cambria Steel Co.†
†Tennessee Coal, Iron & R.R. Co.	Birmingham, Ala.	19″×23″	1 15	8″×8″	13	8	1	......	22	5^m to 6^m	

NOTE. — Information from R. W. Hunt & Co., except that marked (*), which was obtained direct from manufacturers by the committee.

† Compiled by author.

sizes ever constructed for industria service. These are housed in a separate bay, or lean-to, running parallel with the rolls. The rotors are 20 feet in diameter and have a speed of 83 revolutions per minute. All of the motors are connected directly to the roll trains by regular mill couplings. Although the motors are provided with flywheels and run in one direction, provision is made for reversing in case of necessity. The control system has been worked out with the greatest nicety, all operations being under the instant control of the operator by means of a master controller.

The first group of rolls consists of four stands of continuous 40-inch mills,

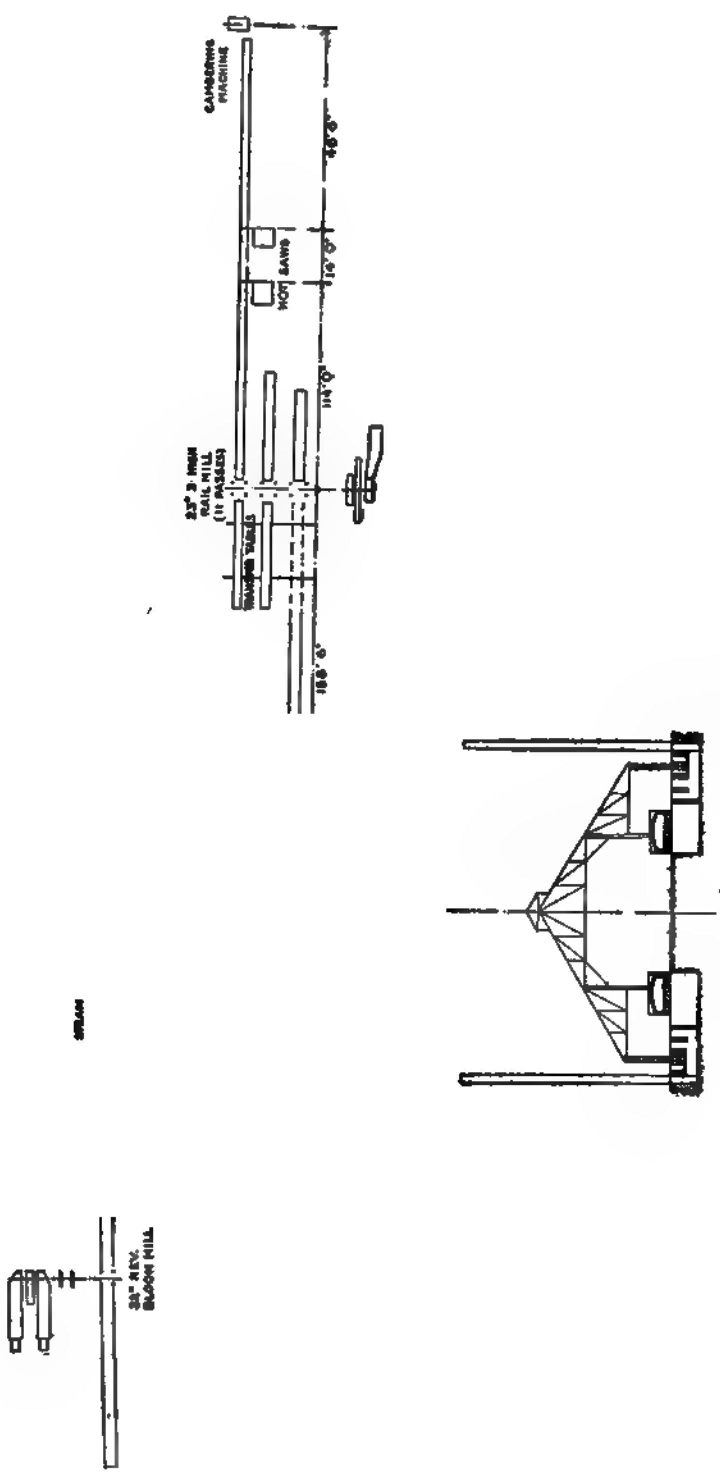


FIG. 323. — Rail Mill, Algoma Steel Company.

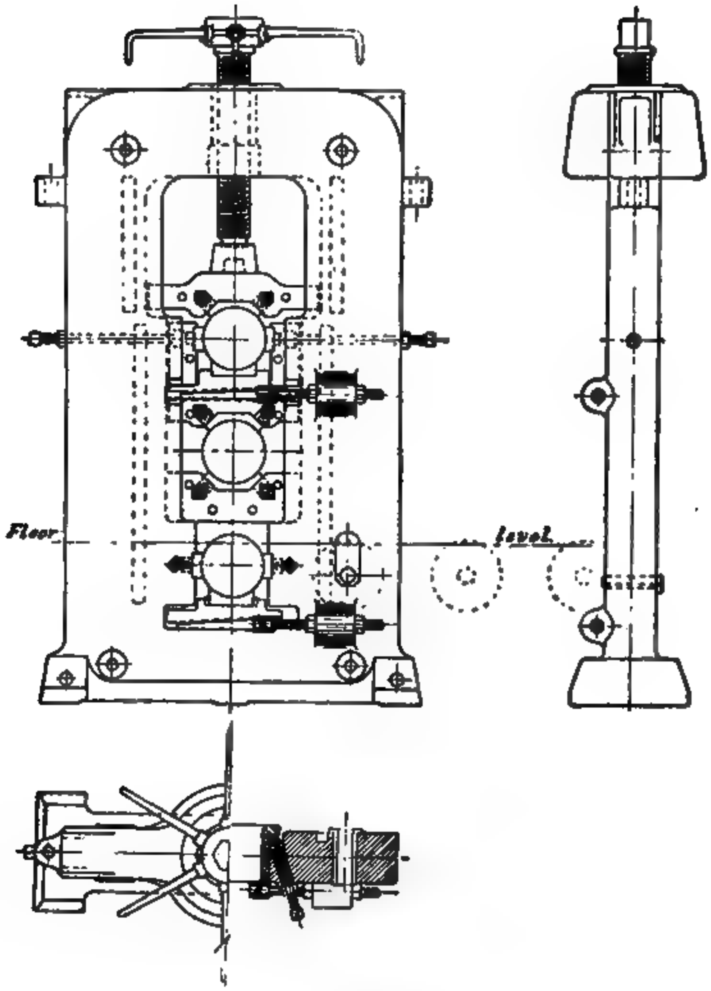
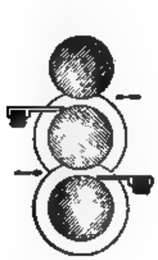


FIG. 324. — Housing for 28-inch Three-high Mill. (Harbord and Hall.)



English Three-high Rail Mill. American Three-high Rail Mill.

FIG. 325. — Rolls used in Three-high Rail Mills. (Harbord and Hall.)

each two of which are driven by a 2000-h.p. motor. They are arranged in tandem, requiring no manipulation from stand to stand. Here, as elsewhere through the plant, sufficient distance is left between successive sets of rolls to enable a quarter turn of the ingot or bloom to be made, so that it is worked equally on all sides. The first two mills are equipped with 42-inch rolls, enabling 20-inch by 24-inch ingots to be used. After passing these four mills the ingot is sent to a 40-inch three-high blooming mill equipped with lifting

Fig. 326. — Three-high Rolls in the Rail Mill at Gary. (Scientific American.)

tables and arranged with a combined hydraulic and pneumatic balancing device. This mill, which is driven by a 6000-h.p. motor, gives the ingot five passes.

After being bloomed the ingot is sheared in a 10-inch by 10-inch horizontal blooming shear, and the crop ends or butts are taken outside of the mill by a butt conveyor of unusual construction, which was designed and built by the engineers of the Indiana Steel Company. Each bloom then goes through a 28-inch roughing mill, which is three-high and equipped with tilting tables. This mill has three stands or rolls. The roughing stand, however, is the only one that is three-high, the other two stands being two-high. The mill is driven

by a 6000-h.p. motor and gives the bloom three passes. After leaving the roughing mill the bloom goes through a two-high 28-inch forming mill driven by a 2000-h.p. motor, receiving but one pass. Then it is sent to finishing mills, which consist of five stands of 28-inch mills driven by two 6000-h.p. motors.

After the dummy pass, the bloom is transferred to the first edging, which is in this same mill but the second stand, and turns back on an elevated table to the second edging, which is in line with the 28-inch roughing mill. It then travels by chain transfer to the lower tables and on the leading pass goes through

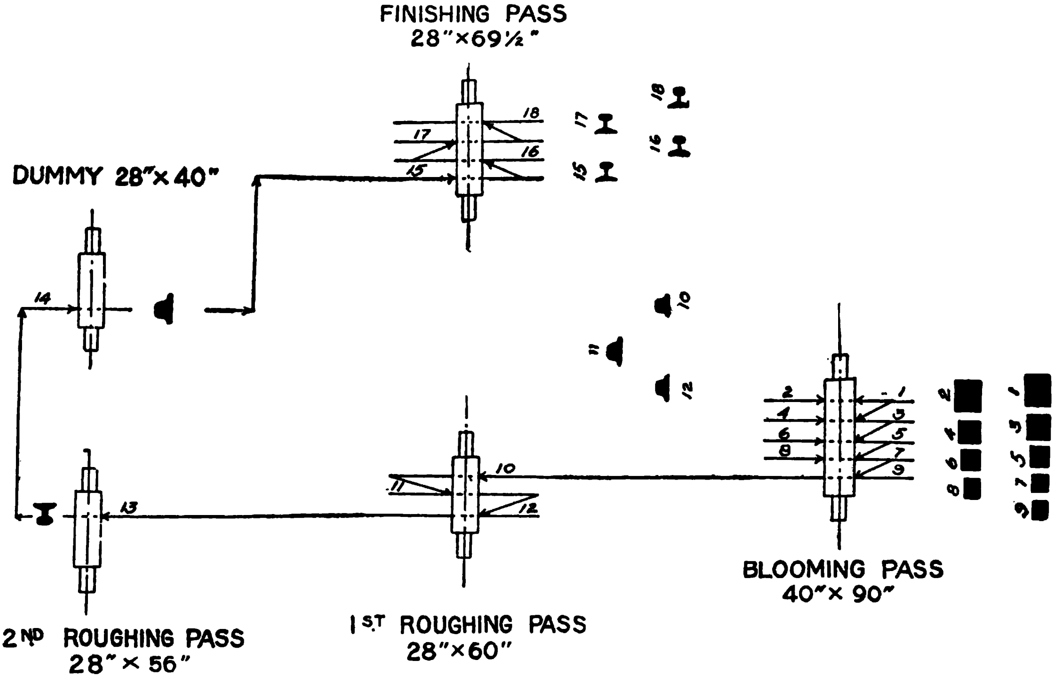


FIG. 327. — Pass Diagram, Rail Mill, Illinois Steel Company, South Works.

a stand, which is also in line with the roughing mill and driven by the same motor, and continues on to the third stand of the 28-inch finishing mill, this being the eighteenth and last pass. After the finishing pass the rail travels through to the saws, of which there are five provided, thus cutting four rails to length. These four rail lengths consist of half the ingot. As the capacity of this mill is 4000 gross tons per 24 hours, it will be seen that there must be a four-rail length sawed about every half-minute. The saws have 42-inch blades, arranged to be raised and lowered in unison by one controller from the hot-saw operator.

The pass diagram of the rail mill at the South Works plant of the Illinois Steel Company is illustrated in Fig. 327. The Bessemer ingot is 18 inches by

FIG. 328. — Rail Mill, Illinois Steel Company, South Works.

$19\frac{1}{2}$ inches, the heating capacity is 192 ingots (24 single-hole pits). The ingot is worked direct to rail without reheating. The blooming mill is 40-inch pitch diameter three-high, and the ingot is given 9 passes and reduced to an 8-inch by 8-inch or 8-inch by $8\frac{1}{2}$-inch bloom. The number of rail lengths rolled are three and four.

The finishing mill consists of one stand 28-inch P. D. three-high first roughing rolls, one stand 28-inch P. D. two-high second roughing rolls, one stand 28-inch P. D. two-high dummy rolls,one stand 28-inch P.D. three-high finishing rolls.

The number of passes from ingot to rail is as follows:

	Passes.
Blooming	9
First roughing	3
Second roughing	1
Dummy	1
Finishing	4
Total	18

Fig. 328 presents the general arrangement of the rail mill.

Table XCV shows the shrinkage allowed by American rail mills and Fig. 329 the lengths of saw runs.

TABLE XCV. — SHRINKAGE ALLOWED BY AMERICAN RAIL MILLS

(Compiled by Committee on Rail, Am. Ry. Eng. Assn., 1909, and revised by the author 1912)

No. of Mill.	Rail Mill.	Location.	Time of Saw Runs.†	Shrinkage Allowed by Mills on 33-foot Rails. Inches.						
				70	75	80	85	90	95	100
1	Algoma Steel Co.	Canadian Soo, Canada.	35	.....	.....	$6\frac{1}{4}$	$6\frac{1}{4}$	.....	.....	.....
2	*Bethlehem Steel Co.	Bethlehem, Pa.	20	6	$6\frac{1}{16}$	$6\frac{1}{2}$	$6\frac{3}{16}$	$6\frac{1}{4}$	$6\frac{5}{16}$	$6\frac{3}{8}$
3	*Cambria Steel Co.	Johnstown, Pa.	17–19	$5\frac{3}{8}$	.....	$5\frac{7}{16}$	.....	$5\frac{9}{16}$	.....	$5\frac{5}{8}$
4	Carnegie Steel Co.	Braddock, Pa.	12–14	.....	.....	$6\frac{3}{16}$	$6\frac{1}{4}$	$6\frac{3}{8}$	.....	$6\frac{5}{8}$
5	Carnegie Steel Co.	Braddock, Pa.	.....	$7\frac{3}{8}$	.....	.....	.....	.....	.....	.....
6	Carnegie Steel Co.	Youngstown, Ohio.	12–17	6	$6\frac{1}{8}$	$6\frac{1}{4}$	$6\frac{5}{16}$	$6\frac{3}{8}$	.....	.....
7	Colo. Fuel & Iron Co.	Pueblo, Colo.	32	$6\frac{1}{2}$	$6\frac{5}{8}$	..	$6\frac{3}{4}$	$6\frac{7}{8}$	.....	.....
8	Dominion Iron & Steel Co.	Sydney, Canada	.....	.....	.....	$6\frac{1}{4}$	$6\frac{3}{8}$	.....	.....	$6\frac{1}{2}$
9	*Illinois Steel Co.	South Chicago, Ill.	17	6	.....	$6\frac{3}{16}$	.....	$6\frac{5}{16}$	.....	$6\frac{7}{16}$
10	Indiana Steel Co.	Gary, Ind.	10–20	.....	.....	.....	.....	$6\frac{7}{16}$	.....	.....
11	*Lackawanna Steel Co.	Buffalo, N. Y.	16	$6\frac{1}{8}$	.....	$6\frac{1}{4}$	.....	$6\frac{3}{8}$	.....	$6\frac{1}{2}$
12	*Maryland Steel Co.	Sparrows Point, Md.	26	$5\frac{3}{4}$	.....	$5\frac{3}{4}$	.....	6	.....	6
13	*Pennsylvania Steel Co.	Steelton, Pa.	5	$6\frac{3}{8}$	.	$6\frac{1}{2}$	.....	$6\frac{5}{8}$	.....	$6\frac{3}{4}$
14	Tenn. Coal, Iron & R.R. Co.	Birmingham, Ala.	27	$6\frac{9}{16}$	$6\frac{5}{8}$	$6\frac{11}{16}$	$6\frac{3}{4}$	$6\frac{7}{8}$	.....	.....

NOTE. — Information from R. W. Hunt & Co., except that marked (*), which was obtained direct from manufacturers by the committee.

† Time is seconds consumed from the time rail leaves finishing rolls till saw drops.

After leaving the saw the rails pass through the cambering machine and are given a head sweep (Fig. 330) of from 3 to 8 inches, the A. S. C. E. section

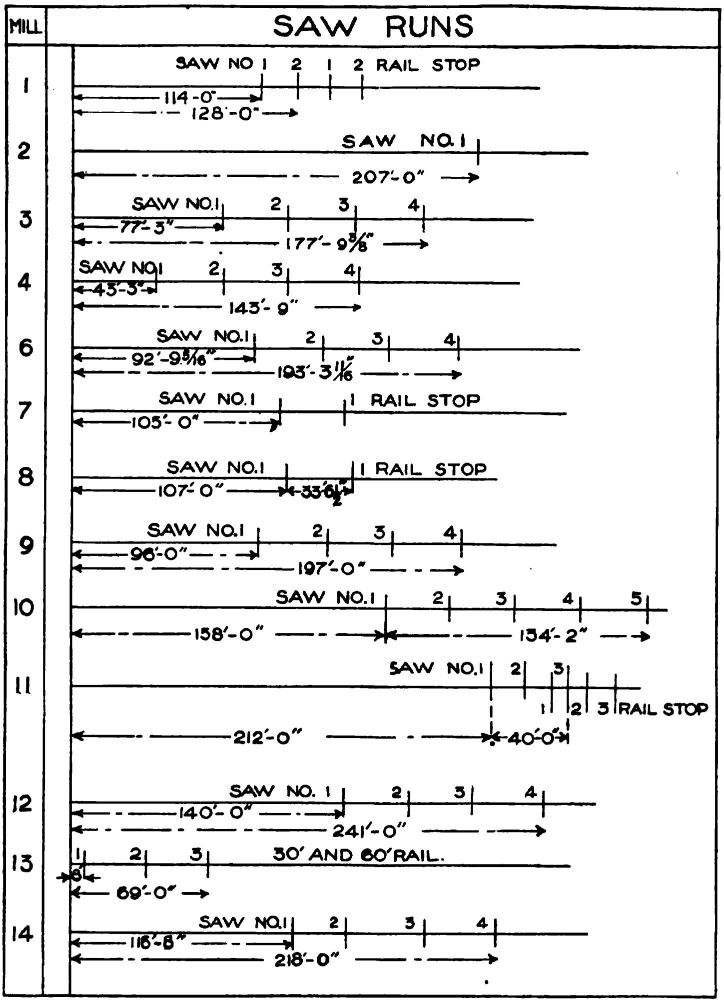


FIG. 329. — Saw Runs of American Rail Mills. (See Table XCV for number of mills.)

requiring a greater ordinate than the A. R. A. rails. The rails then pass to the hot beds and after being allowed to cool are transferred to the gagging or cold-straightening presses (Fig. 331).

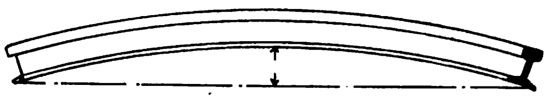


FIG. 330. — Head Sweep.

In the heavier A. S. C. E. sections the gagging or straightening of the rail after it leaves the rolls and is cooled in the hot beds tends to develop injurious strains in the base and web. In some of the most modern English plants the

rails are run while still hot through straightening rolls, thus much reducing the labor of final straightening.*

FIG. 331. — Cold Straightening Press, Maryland Steel Company.

After straightening, the rails are inspected, drilled, reinspected, and loaded on cars for shipment. Many rails were formerly damaged in loading, but at several mills the use of a magnetic crane is now employed for loading the rails.

The brand on rails gives the name of the manufacturer, a number or abbreviation by which the rail section is designated, the month and year of manufacture,

* S. von Schukowski advocates straightening rails while still hot. Das richten von eisenbahnschienen im katten und warmen zustande. Stahl und Eisen, Vol. 27 (1907), Pt. 1, p. 797.

and, if the metal is open-hearth steel, the letters "O. H." are also added. Sometimes the letters "F. T." are added to signify ferro-titanium steel. Square block letters and figures about one inch high are commonly used, and, as these are cut into one of the rolls of the last pass, the brand will always appear slightly raised at regular intervals on the web of the rail. The month is generally shown by Roman numerals, as VII for July, and sometimes by a series of I's, as IIIII for May.

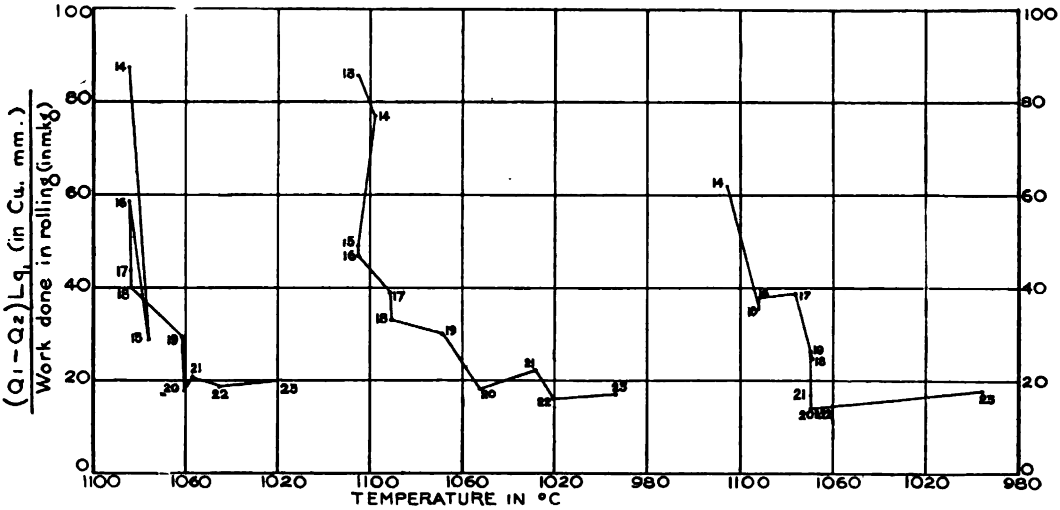


FIG. 332. — Value of V/E for Tables XCVI, XCVII and XCVIII.

The number representing the heat, blow or melt of steel, and the letter to indicate the position of the rail in the ingot is stamped on the web of the rail with dies while it is still red hot, but after it has been completely rolled and sawed to length. As the brand always appears in raised letters, and the heat number and letter is stamped on no confusion of the two should exist.*

A series of experiments were made in Germany by Dr. Puppe† to determine the power required to roll different sections. As this investigation presents many features connected with the design of the section and rolls and the effect of the temperature on rolling, it will be of interest to briefly review Dr. Puppe's work as it relates to the heavier weights of rails examined.

The reversing mill on which these tests were made consisted of one cogging mill housing and three finishing mill housings. A flywheel converter set of the Ilgner system served to equalize the fluctuations of the power taken. The mill was driven by three motors rigidly coupled together, and connected in

* R. W. Hunt and Company, 1121, The Rookery, Chicago, Ill., have published in convenient form full information in regard to the practice of branding and stamping at the different mills.

† Experimental Investigations on the Power Required to Drive Rolling Mills, J. Puppe, London, 1910. See also for a full treatise of this subject Steel, Harbord and Hall, London, 1911, pp. 666–741.

series electrically; they had an aggregate output of 3600 H.P. normal and 10,350 H.P. maximum at a speed of 110 r.p.m.

Tables XCVI, XCVII and XCVIII contain the results of the tests with the heavier rails. The second line of the tables gives the time taken by the pass (in seconds) determined from the rise and fall of the current and power curves.

Line 3 gives the time intervals (in seconds) between successive passes which were determined in the same way as the times of the passes. The time interval between the first and second passes is given in the column headed "pass 1," that between second and third passes in the column headed "pass 2," and so on. The last column contains the sum of all the figures in the preceding columns.

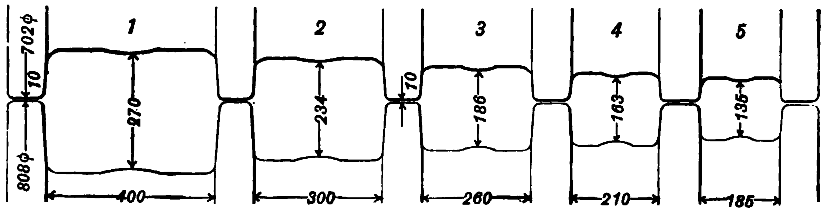


FIG. 333. — Diagram of Cogging Rolls, Tables XCVI, XCVII and XCVIII, Dimensions in Millimeters.

The energy given up, or stored by, the flywheel and other rotating masses was calculated from the speed curves and the moments of inertia.

To arrive at the light-load loss, the average speed was determined, and the light-load loss was obtained by multiplying the power taken to drive the mill light at this speed by the time.

The total work done in rolling the bar up to any pass is the sum of the work done in each individual pass up to that point, taking due account of the motor efficiency and leaving out the work expended in accelerating the moving parts or in light-load losses, copper losses, etc. Frequently, the section of the ingot during the first few passes could be determined only roughly, and then the length of the bar after the second or third pass was taken as unity, and the summation of the work done in rolling commenced correspondingly later.

The areas of the cross sections of the bar or ingot were obtained wherever possible by cutting trial pieces off the bar, and measuring the area directly by a planimeter. It was not always possible to cut samples from the bars during the roughing passes, as the bar was too large for the bloom shears or hot saws, and in such cases the cross-sectional area was obtained from the scale showing the position of the rolls, while sections were cut from the bar in the last two passes, and the area measured as a check. It is often found that billets are

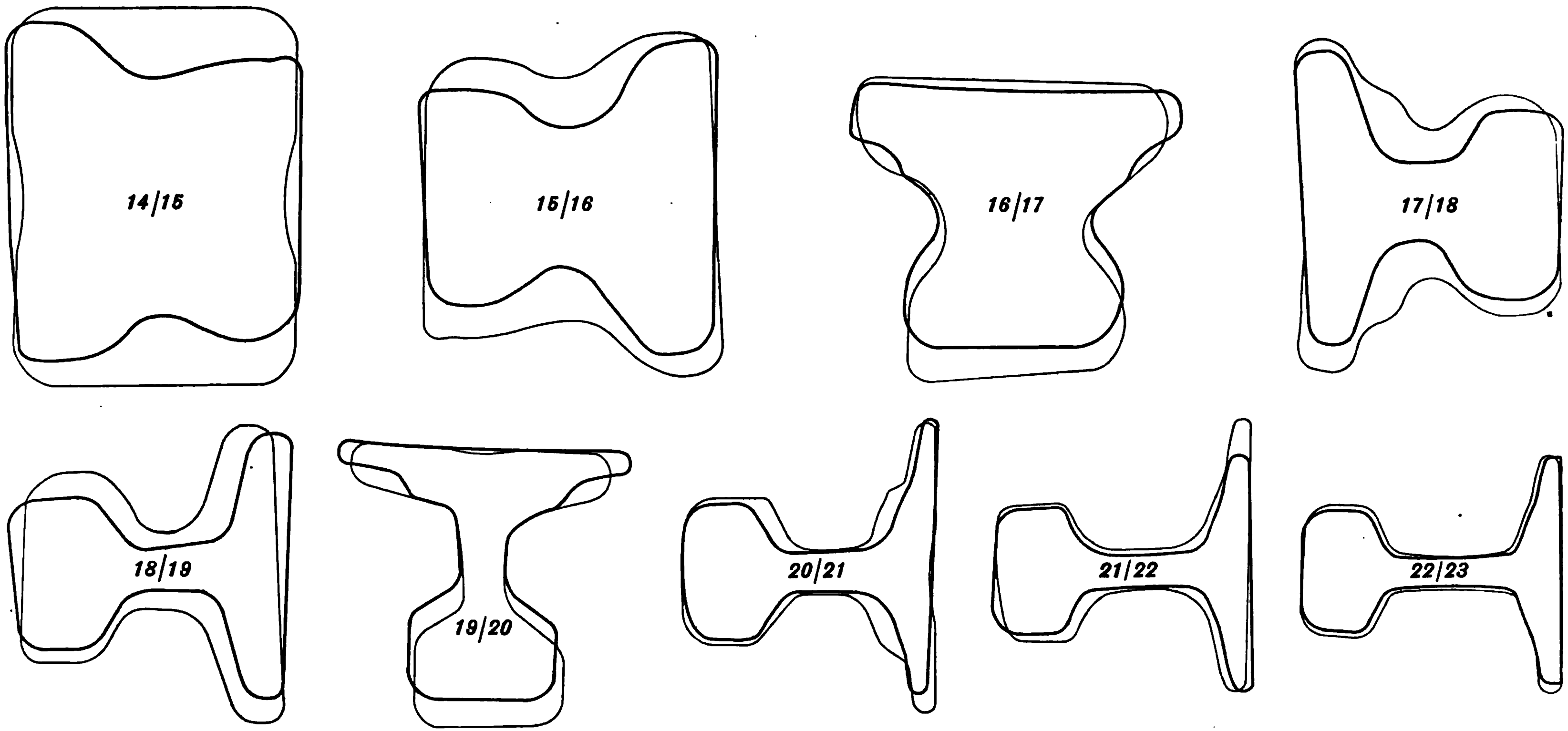


Fig. 334. — Bar Sections of Passes 14 to 23. Scale about 1 : 3.45 (Tables XCVI, XCVII and XCVIII.)

TABLE XCVI.—ROLLING RAILS FOR THE NORTH AUSTRIAN RAILWAYS, ABOUT 35.5 KG. PER METER

(Power Required to Drive Rolling Mills.)—J. Puppe.

1	Number of Pass.	1	2	3	4	5	6	7	8	9	10	11	12
2	Duration of pass, secs.	2.8	4.4	3.73	3.42	3.47	3.22	3.44	4.56	4.78	4.23	4.7	4.69
3	Interval between passes, secs.	7.5	7.6	7.43	10.85	7	6.48	7.04	8.87	7.65	10	8.61	11.3
4	R.p.m. Initial	14.2	20.3	18.8	20.4	12.3	22.3	20.7	21.4	17.6	19.4	14.3	22.3
	R.p.m. Maximum	...	...	...	...	...	...	...	...	...	...	...	...
	R.p.m. Final	28.2	32.5	40.1	47.2	41	45.2	40	40.6	38.5	46.9	54.1	56.4
5	Average r.p.m.	20	16.9	20.9	26.8	21.4	30	26.2	23.8	24.6	29.5	30.1	30.3
6	Energy supplied to the rotating masses, H.P.-secs.	221	239	498	676	570	576	437	444	437	680	1,015	1,002
7	Energy given up by the rotating masses, H.P.-secs.	...	...	...	...	...	...	...	...	...	...	...	...
8	Average input of motor, H.P.	1,188	1,072	1,372	1,395	1,429	1,530	1,580	1,530	1,834	1,606	1,868	1,594
9	Maximum input of motor, H.P.	1,862	1,408	2,230	2,208	2,730	2,441	2,496	2,644	2,918	2,478	3,224	2,628
10	Average copper loss, H.P.	270	348	325.3	286	312.9	261	327.2	348	434.8	290.2	355	256.5
11	Maximum copper loss, H.P.	435	503	503	435	492	412	515	515	391	435	565	404
12	Average light-load loss of mill, H.P.	95	80	100	128	100	141	124	114	118	141	141	141
13	Energy consumed by motor, H.P.-secs.	3,325	4,714	5.114	4,770	4,956	4,925	5,440	6,978	8,760	6,798	8,778	7,475
14	Work of acceleration, H.P.-secs.	221	239	498	676	570	576	437	444	437	680	1,015	1,002
15	Light-load losses, H.P.-secs.	266	352	373	438	347	454	426	520	565	596	663	661
16	Copper losses, H.P.-secs.	755	1,532	1,212	977	1,086	840	1,125	1,588	2,080	1,228	1,668	1,250
17	Work done in rolling, H.P.-secs.	2,083	2,591	3,031	2,679	2,953	3,055	3,452	4,426	5,678	4,294	5,430	4,562
18	Work done in rolling (In per cent of the motor input)	62.8	55	59.3	56.2	59.5	62	63.5	63.3	64.8	63	61.8	61.2
19	Work done for acceleration (In per cent of the motor input)	6.7	5.08	9.74	14.2	11.5	11.7	8.04	6.37	4.98	10	11.6	13.4
20	Light-load losses (In per cent of the motor input)	8	7.47	7.3	9.2	7	9.2	7.8	7.45	6.45	8.8	7.55	8.85
21	Total work done in rolling, H.P.-secs.	2,083	4,674	7,705	10,384	13,337	16,302	19,844	24,270	29,948	34,242	39,672	44,234
22	Shape of the pass*												
23	Dimensions of pass, mm.	395×405	360×409	320×413	285×417	350×289	300×293	290×297	245×301	242×249	202×253	207×206	174×210
24	Sectional area of ingot or bar, sq. cm.	1,599.75	1,472.4	1,321.6	1,188.45	1,011.5	879	861.3	737.5	602.6	511	426.4	365.4
25	Reduction of area, sq. cm.	143.25	127.35	150.8	133.15	176.95	132.5	11.7	123.8	134.9	91.6	84.6	61
26	Length of ingot or bar, meters	1.474	1.602	1.788	1.988	2.332	2.687	2.74	3.2	3.915	4.615	5.53	6.46
27	Elongation	1.09	1.18	1.32	1.47	1.72	1.98	2.025	2.36	2.895	3.41	4.08	4.77
28	Volume displaced $[(Q_1-Q_2)\ L_{q_1}]$ in cu. cm.	19,110	18,771.39	24,158.16	23,807.22	35,177.66	30,899	31,613.4	33,921.2	43,168	35,861.4	39,042.9	33,733
29	$\frac{(Q_1-Q_2)\ L_{q_1}\ \text{(in cu. mm.)}}{\text{Work done in rolling (in m. kg.)}}$	122.7	96.4	106.1	119.0	159.1	135.2	122.2	102.2	101.4	111.2	96	98.6
30	Temperature in °C.	1,145	1,145	1,145	1,139	1,139	1,133	1,126	1,119	1,112	1,105	1,098	1,098

* The first 14 passes are cogging passes.

REMARKS.—Initial section, 445×415 mm. at the bottom, and 415×395 mm. at the top; initial length, 1352 meters. Material, Siemens-Martin steel. Finished weight, 1852 kg. Chemical composition—C, 0.38 per cent; P, 0.051 per cent. Tensile strength, 67.4 kg. per sq. mm.; contraction, 38.0 per cent; elongation, 23.0 per cent.

The ingot was turned in the cogging mill after passes 4, 8, 10, 12, and 13. The first roughing pass was rolled on edge with the ingot 132×176 mm. The sectional area of the cogging passes was determined from the position of the upper roll; and that of passes 15, 16, 17, 18, and 19, from direct measurement of the bar. The volume displaced was calculated separately for the first pass.

For diagram see Fig. 332. For sketch of the cogging rolls see Fig. 333, and for the profile sections see Fig. 334.

TABLE XCVI (Concluded). — ROLLING RAILS FOR THE NORTH AUSTRIAN RAILWAYS, ABOUT 35.5 KG. PER METER

(Power Required to Drive Rolling Mills.) — J. Puppe.

1	Number of Pass.	13	14	15	16	17	18	19	20	21	22	23	Total.
2	Duration of pass, secs.	5 26	9 08	7.6	6.4	7 73	8 94	10 75	10 22	12.2	13.43	13.74	152 73
3	Interval between passes, secs	16 93	17	8.35	7 98	10 9	22 2	8 22	8 22	8.14	11 6	...	219 87
4	R.p.m. … Initial	14 4	14 2	9 2	20.9	20 4	19.8	15	24 3	20.1	24.3	17 4	
	Maximum							85 5	108 7	97.2	108.5	115.6	372 60
	Final	60 9	55 6	66 9	79 9	81 2	79	83.3	105 6	89 4	99 1	109 5	
5	Average r.p.m.	36 4	27 8	42 6	58 7	60 5	54 2	68	75 3	77.5	76 2	89	
6	…passes, H.P.-secs	1,306	1,077	1,637	2,217 5	2,303.5	3,180	2,642	4,185.5	3,207	3,774	4,671	36,194 5
7	…masses, H.P.-secs							138	247 5	543	332	512	1,773.5
8		1,536	1,578	2,740	2,728	1,757	2,844	3,078	2,190	3,104	2,505	2,102	
9		2,680	2,744	3,944	3,824	2,542	3,932	3,958	3,020	2,725	3,306	3,360	34,423
10		191 5	267 8	376	244	101 3	369 4	231 4	105.2	201.3	139 6	95 8	
11		322	411	590	473	160	435	392	201	404	344	319	
12	…I.P.	174	132	205	281	291	260	325	360	372	364	427	
13	…-secs	8,068	14,238	20,810	17,452	13,566	25,416	33,106	22,403	37,900	33,674	26,917	326,606
14		1,306	1,077	1,637	2,218	2,308	2,180	2,508	3,938	2,664	3,442	4,350	
15		915	1,191	1,560	1,798	2,342	2,322	3,465	3,680	4,540	4,890	5,870	
16		1,006	2,418	2,860	1,562	781	2,406	2,488	1,073	2,450	1,874	1,317	
17		4,360	9,542	14,753	11,874	8,240	18,508	24,622	13,712	28,246	23,468	17,371	223,856
18	… in per cent of the motor input	60 2	67	71	68	60 7	72 7	74 5	61 3	74 5	69.6	60	
19	Work done for acceleration, in per cent of the motor input	16 2	7.56	7.86	12 7	17	8 6	7.57	17.5	7.04	10.2	15	
20	Light-load losses, in per cent of the motor input	11 3	8.4	7 5	10.3	16 5	9.15	10 5	16.4	12	14.5	20.3	
21	Total work done in rolling, H.P.-secs.	49,094	58,636										
22	Shape of the pass*												
23	Dimensions of pass, mm.	172×178	133×176										
				Roughing Mill.				Finishing Mill					
				Forming Pass.	Forming Pass.	Swabbing Pass.	Forming Pass.	Forming Pass.	Swabbing Pass.	Finishing Pass.	Finishing Pass.	Finishing Pass.	
24	…cm.	316 8	232.32	209 3	156 1	136 3	108	81 1	74.6	60.8	52.3	46 5	
25		48 6	34 48	32 02	44 2	17 8	32 5	24 9	6.5	13.8	8.5	5 8	
26		7 45	10 17	11 77	15 1	17 05	22 24	29 1	31 64	38 63	45.1	50.75	
27		5 50	7 50										
28	…in cu. cm.	31,395.6	62,937 6	32,564 34	52,023.4	26,678	55,412 5	55,377 6	18,915	43,663.2	32,997	26,158	
29		66	67 9	29 4	58.5	43.5	39 9	29.9	18.4	20 6	18.75	20.1	
30		1,091	1,064	1,076	1,064	1,064	1,064	1,061	1,061	1,057	1,045	1,021	

* The first 14 passes are cogging passes.

TABLE XCVII. — ROLLING RAILS FOR THE NORTH AUSTRIAN RAILWAYS, ABOUT 35.5 KG. PER METER

(Power Required to Drive Rolling Mills.) — J. Puppe.

1	Number of Pass.	1	2	3	4	5	6	7	8	9	10	11	12
2	Duration of pass, secs.	2.88	2.82	3.38	2.97	3.17	3.62	3.51	3.78	4.35	5.14	4.49	6.08
3	Interval between passes, secs.	7.55	9.30	8.69	10.52	10.18	6.12	7.50	8.37	7.16	9.49	8.30	11.21
	R.p.m. Initial	9.7	19.3	16.3	22.9	12.2	16.9	14.8	17.7	14.2	17.9	14.2	14.0
4	R.p.m. Maximum												
	R.p.m. Final	26.1	33.5	45.3	52.7	35.1	46.7	43.8	47.3	43.8	40.6	59.5	54.8
5	Average r.p.m.	26.5	22.5	25	28	20	26.5	25	28.5	22	25	31	24.5
6	Energy supplied to the rotating masses, H.P.-secs.	218.9	279.6	666.1	839.7	427.7	716.9	623.5	618.6	640.1	495.2	1,244.8	1,146.7
7	Energy given up by the rotating masses, H.P.-secs.												
8	Average input of motor, H.P.	1,187	1,183	1,407	1,476	1,166	1,261	1,239	1,339	1,611	1,404	1,547	1,260
9	Maximum input of motor, H.P.	2,250	1,971	2,680	2,550	2,181	2,440	2,342	2,466	2,848	2,305	3,066	2,748
10	Average copper loss, H.P.	225	264	321	254	263	245	241	286	344	271	257	198
11	Maximum copper loss, H.P.	392	412	515	404	424	383	404	383	515	413	444	392
12	Average light-load loss of mill, H.P	128	110	118	132	95	128	118	136	105	118	146	118
13	Energy consumed by motor, H.P.-secs	3,419	3,339	4,753	4,385	3,695	4,565	4,350	5,055	7,005	7,220	6,950	7,660
14	Work of acceleration, H.P.-secs.	219	280	666	840	428	717	623.5	619	640	495	1,245	1,147
15	Light-load losses, H.P.-secs.	368	310	398	392	301	463	414	514	457	606	655	717
16	Copper losses, H.P.-secs.	648	745	1,083	755	834	887	846	1,080	1,495	1,391	1,152	1,203
17	Work done in rolling, H.P.-secs.	2,184	2,004	2,606	2,398	2,132	2,498	2,467	2,842	4,413	4,728	3,898	4,593
18	Work done in rolling (In per cent of the motor input)	63.8	60	54.7	54.6	57.7	54.7	56.7	56.2	63	65.5	56	59.8
19	Work done for acceleration (In per cent of the motor input)	6.4	8.4	13.9	19.2	11.6	15.7	14.3	12.3	9.14	6.85	17.9	14.9
20	Light-load losses (In per cent of the motor input)	10.8	9.15	8.4	8.95	8.15	10.1	9.5	10.2	6.5	8.4	9.4	9.35
21	Total work done in rolling, H.P.-secs.	2,184	4,188	6,794	9,192	11,324	13,822	16,289	19,131	23,544	28,272	32,170	36,763
22	Shape of the pass*												
23	Dimensions of pass, mm.	395×405	355×409	325×413	290×417	350×294	310×298	285×302	245×306	247×249	197×253	212×201	172×205
24	Sectional area of ingot or bar, sq. cm.	1,599.75	1,451.95	1,342.25	1,209.30	1,029.0	923.8	860.7	749.7	615.0	498.4	426.1	352.6
25	Reduction of area, sq. cm.	143.25	147.8	109.7	132.95	180.6	105.2	63.1	111.0	134.7	116.6	72.3	73.5
26	Length of ingot or bar, meters	1.428	1.571	1.7	1.89	2.22	2.451	2.655	3.05	3.72	4.58	5.36	6.48
27	Elongation	1.09	1.20	1.30	1.44	1.695	1.89	2.025	2.325	2.835	3.50	4.09	4.95
28	Volume displaced $[(Q_1-Q_2)\,L_{q_1}]$ in cu. cm.	18,530	21,105.84	17,233.87	22,601.5	34,133.4	23,354.4	15,465.81	29,470.5	41,063.5	43,375.2	33,113.4	39,396.0
29	$\frac{(Q_1-Q_2)\,L_{q_1}\text{ (in cu. mm.)}}{\text{Work done in rolling (in m. kg.)}}$	113.2	140.8	88.5	125.6	213.8	124.7	83.7	138.2	124.0	122.2	113.6	115.0
30	Temperature in °C.	1,169	1,163	1,163	1,157	1,157	1,157	1,145	1,145	1,139	1,133	1,126	1,119

* Passes 1 to 14 are cogging passes.

Remarks. — For dimensions of ingot, etc., see Table XCVI. Finished weight, 1790 kg. Initial length, 1308 meters.

TABLE XCVII (Concluded). — ROLLING RAILS FOR THE NORTH AUSTRIAN RAILWAYS, ABOUT 35.5 KG. PER METER

(Power Required to Drive Rolling Mills.) — J. Puppe.

1	Number of Pass.	13	14	15	16	17	18	19	20	21	22	23	Total.
2	Duration of pass, secs	4 88	11.22	7 72	7 26	6 34	8 78	10 26	9 09	12 00	13.82	13.82	152 38
3	Interval between passes, secs	34 50	20 42	8 80	9 87	20 70	20 65	18 60	33 15	8 70	12 64		287 02
4	R.p.m. Initial	14 2	6 4	8 5	18 3	17 4	45 1	13 4	23 3	25 3	19 5	21.7	
	R.p.m. Maximum					99 5		80.3		89 3	99 4	115 6	439.40
	R.p.m. Final	55.6	43 7	63 1	78.7	74 0	80 1	63.2	113 6	86 2	96 3	113 6	
5	Average r.p.m.	28	25	42 5	54	77	58 5	66 5	82	73	74 5	67 5	
6	masses, H.P.-secs	1,077 5	696 7	1,457 7	2,186 3	3,579	1,634	2,906 4	4,609	2,734	3,532 2	4,807	37,137.8
7	masses, H.P.-secs			....		1,649		392 4		192	216 2	171	2,620.6
8		1,390	1,219	2,050	2,804	2,220	3,196	3,121	2,610	2,758	2,750	2,316	
9		1,990	2,099	3,720	3,885	3,773	4,485	3,888	3,480	3,527	3,642	3,440	34,517
10		141	220	369	280	144	296	260	136	233	167	101	
11		197	344	564	434	304	488	444	262	427	373	252	
12	H.P	182	118	202 5	260	368	279	317.5	302	351	357 5	419 5	
13	P.-secs	6,785	13,885	15,825	20,350	14,080	26,050	32,015	23,720	35,820	38,025	32,010	322,791
14		1,077 5	697	1,458	2,186	1,930	1,634	2,514	4,609	2,542	3,316	4,636	
15		887	1,325	1,565	1,869	2,384	2,451	3,255	3,560	4,562	4,940	5,800	
16		688	2,472	2,850	2,033	913	2,512	2,665	1,235	3,030	2,307	1,895	
17		4,133	9,191	9,952	14,272	8,903	21,453	23,581	14,316	25,686	27,462	20,179	215,891
18	In per cent of the motor input	61	67 2	63	70	63 3	76 5	73 5	60 4	71 7	72 2	62 8	
19		15 9	5 1	9 2	10 7	13 7	5 8	7 65	19 4	7 1	8 7	14 5	
20		13 1	9 7	9.9	9 3	16 6	8 75	10.15	15	12 7	13	18.1	
21	-secs....	40,896	50,087										
22				......		..	..	.....	....	....	....	....	
23	Dimensions of pass, mm......	177×176	183×181										
				Roughing Mill				Finishing Mill.					
				Forming Pass.	Forming Pass.	Swabbing Pass.	Forming Pass.	Forming Pass.	Swabbing Pass.	Finishing Pass.	Finishing Pass.	Finishing Pass.	
24	cm........	311 5	238.92	200 2	156.1	138 3	106.0	81.1	74 6	60 8	52 3	46 5	
25		41 1	72 58	38 62	44.2	17 8	32 5	34.9	6 5	13 8	8 5	5.8	
26		7 34	9 55	11 4	14.62	16 51	21 5	29.1	30 55	37 52	43 60	49 06	
27		5 60	7 30	.....		..		...	..	.....	...	.. ..	
28	in cu. cm......	36,632 8	53,273 72	36,882 1	50,388 0	26,063 6	53,658 5	53,535	18,915	42,159	31,902	25,268	
29		85.9	77 3	49 4	47.0	30	33 35	30 3	17 6	21 85	15 5	18 7	
30		1,105	1,098	1,105	1,105	1,091	1,091	1,069	1,053	1,029	1,021	984	

* Passes 1 to 14 are cogging passes.

For diagram see Fig. 332. For sketch of cogging rolls see Fig. 333, and for bar sections see Fig. 334.

TABLE XCVIII. — ROLLING RAILS, ABOUT 35.5 KG. PER METER

(Power Required to Drive Rolling Mills.) — J. Puppe.

1	Number of Pass.	1	2	3	4	5	6	7	8	9	10	11	12
2	Duration of pass, secs.	3.42	5.09	3.91	4.00	4.17	3.48	3.83	3.85	5.04	4.61	6.87	6.12
3	Interval between passes, secs.	7.75	7.48	8.15	19.35	7.66	7.30	7.98	12.13	6.67	11.27	7.79	9.87
4	R.p.m. Initial	5.5	19.5	15	20	10.5	20	10.5	18	9.5	17.5	10.5	19.5
	R.p.m. Maximum												
	R.p.m. Final	34	40.5	34	40	30	50	40	51	44.5	52	49	54
5	Average r.p.m.	11	18.6	17.5	21.8	17	29.4	20	29	16	25.7	20	28
6	Energy supplied to the rotating masses, H.P.-secs.	419.7	469.6	347.1	447.6	294.6	783	555.6	846.8	701.8	894.0	555.6	945.4
7	Energy given up by the rotating masses, H.P.-secs.												
8	Average input of motor, H.P.	629	756	790	995	997	1,379	999	1,439	1,232	1,041	670	1,407
9	Maximum input of motor, H.P.	1,704	1,748	1,637	2,019	1,872	2,238	1,965	2,202	2,572	3,007	1,611	2,465
10		213	268	237	292	260	271	240	227	320	330	178	294.5
11		374	444	407	435	444	413	372	323	541	516	278	382
12	light, H.P.	51	88	82.5	105	80	138	95	136	75	122	96	132
13	secs	2,148	3,848	3,068	3,980	4,160	4,800	3,825	4,100	6,215	7,570	4,600	8,620
14	masses, H.P.-secs.	420	470	347	448	295	783	556	847	702	894	556	945
15		174	448	322	420	334	480	364	523	378	562	663	807
16		729	1,365	926	1,168	1,084	944	920	875	1,007	1,520	1,221	1,803
17	Work done in rolling, H.P.-secs.	825	1,565	1,493	1,944	2,447	2,693	1,985	1,855	3,528	4,883	2,170	5,065
18	Work done in rolling (In per cent of the motor input)	33.4	40.7	48.4	48.9	58.8	56.1	51.9	45.2	56.7	64.4	47.2	67.7
19	Work done for acceleration (In per cent of the motor input)	19.5	12.2	11.2	11.2	7.1	16.3	14.5	20.6	11.3	11.8	12.1	10.9
20	Light-load losses (In per cent of the motor input)	8.1	11.6	10.4	10.5	8	10	9.5	12.7	6.1	7.4	14.2	9.4
21	Total work done in rolling, H.P.-secs.	825	2,390	3,883	5,827	8,274	10,967	12,952	14,807	18,335	23,218	25,388	30,453
22	Shape of the pass*												
23	Dimensions of pass, mm.	380×382	355×386	327×390	295×294	355×209	315×303	275×307	255×311	252×259	202×263	222×206	177×210
24	Sectional area of ingot or bar, sq. cm.	14,516	1,370.3	1,275.3	1,161	1,061.45	954.45	844.25	793.05	652.7	531.25	457.3	371.7
25	Reduction of area, sq. cm.		145.7	95	114.3	99.55	107	110.2	51.2	140.35	121.45	73.95	85.6
26	Length of ingot or bar, meters	1.675	1.745	1.873	2.508	2.245	2.5	2.83	3.01	3.66	4.5	5.215	6.42
27	Elongation		1.05	1.13	1.24	1.36	1.51	1.71	1.82	2.22	2.72	3.16	3.89
28	Volume displaced $[(Q_1-Q_2)L_{q_1}]$ in cu. cm.	3,420	15,270	16,577.5	21,408.4	20,487.4	24,021.5	27,550	14,480.6	42,245.3	44,450.7	33,277.5	44,640.4
29	$\frac{(Q_1-Q_2)L_{q_1} \text{ (in cu. mm.)}}{\text{Work done in rolling (in m. kg.)}}$	81.7	130	148	146.8	111.7	119	185	104	159.7	121.2	204.2	117.6
30	Temperature in °C	1,157	1,157	1,151	1,145	1,133	1,126	1,126	1,119	1,105	1,084	1,084	1,077

* The first 14 passes are cogging passes.

REMARKS. — Initial section, 400×400 mm. at the bottom, and 360×360 mm. at the top; initial length, 1653 meters. Material, Siemens-Martin rail steel. Finished weight, 1875 kg. Chemical composition — C, 0.44 per cent; P, 0.064 per cent; tensile strength, 69.8 kg. per sq. mm.; contraction, 29.4 per cent; elongation, 16.0 per cent.

For diagram see Fig. 332. For sketch of cogging rolls see Fig. 333 and for the bar sections see Fig. 334.

TABLE XCVIII (Concluded). — ROLLING RAILS, ABOUT 35.5 KG. PER METER

(Power Required to Drive Rolling Mills.) — J. Puppe.

1	Number of Pass.	13	14	15	16	17	18	19	20	21	22	23	Total.
2	Duration of pass, secs.	6.64	6 60	8 06	7 72	6.35	10.42	10.48	8 26	13.03	12 49	14 83	159 25
3	Interval between passes, secs	12 75	22 18	9 13	8 84	8.99	12.90	7.10	10 19	8.38	9 72	.	223 58
4	R.p.m. Initial	14 5	13	9	20 5	7 5	21.5	14.5	20	15	22	14	382 83
	R.p.m. Maximum	...	...	..	-		87	91	...	96	116	...	
	R.p.m. Final	43	71	67 5	72 5	98 5	70	73	121	91	115	119	
5	Average r.p.m.	25	38	37 4	57 5	65 2	59	58 5	87 2	69	84	68 6	
6	s	610 8	1,816.6	1,668 7	1,803.3	3,596 7	2,649 7	3,009	4,946	3,352 3	4,826 7	5,207	40,748
7	es	...	...				995 2	1,101		349	86 2		2,831
8		1,066	2,360	2,583	3,130	2,455	3,670	3,413	3,344	3,250	3,480	2,024	
9		1,670	3,756	3,930	3,457	3,460	4,625	4,070	3,742	3,664	3,913	3,524	38,217
10		154	297	351	211	114	308 5	202	134	163	162 5	85 5	
11		230	459	515	314	226	615	392	352	322	526	312	
12		118	182	179 5	275	311	281	279	418	330	403	325	
13		7,005	15,565	20,800	24,160	15,590	38,260	35,785	27,610	42,375	43,475	30,000	357,579
14	-secs	611	1,817	1,669	1,803	3,597	1,655	1,908	4,946	3,003	4,751	5,207	
15		583	1,200	1,440	2,123	1,975	2,930	2,922	8,452	4,300	5,035	4,815	
16		1,022	1,960	2,825	1,630	724	3,218	2,116	1,108	2,124	2,030	1,267	
17		4,789	10,588	14,866	18,604	9,294	30,457	28,839	18,106	33,948	31,659	18,711	250,814
18	tor	68 3	68 0	71 5	77 1	59 5	79 6	80 5	65 5	80 1	72 9	62 4	
19		8 7	11 7	8	7.5	23 1	4 3	5 3	17 9	7 1	10 9	17 3	
20		8 3	7 7	6 9	8.8	12.7	7.6	8.2	12.5	10 1	11 6	16	
21		35,242	45,830	....	....	....	....	....	....	....	....	..	
22													
23		172×181	137×185										
				Roughing Mill.				Finishing Mill.					
				Forming Pass.	Forming Pass.	Swabbing Pass	Forming Pass.	Forming Pass.	Swabbing Pass.	Finishing Pass.	Finishing Pass.	Finishing Pass.	
24	ı. cm.	311.3	241 12	200 3	156 1	138 5	108	81 1	74.6	60.8	52.3	46.7	
25		60 4	70 18	40 82	44 20	17 6	32.5	24 9	6.5	13 8	8.5	5 6	
26		7.665	9.92	11 92	15 3	17 25	22.5	29 45	32	39.3	45.7	51.1	
27		4 64	5 99			...	...						
28	in cu. cm.	38,776 8	53,792 97	40,493 44	52,686 4	26,928	56,062 5	56,025	19,142 5	44,160	33,405	25,592	
29		107 9	81.9	36 4	37.75	38 6	24 5	25 9	14.1	17.35	14 0	18.2	
30		1,084	1,105	1,091	1,091	1,076	1,069	1,069	1,069	1,069	1,069	994	

* The first 14 passes are cogging passes.

The bar was turned 90° after passes 4, 8, 10, 12, 13, and 14. The first roughing pass (15) was rolled on edge. The "volume displaced" was separately calculated for passes 1, 2, and 5, on account of the irregular shape of the ingot, and the sectional areas given are calculated from the position of the upper roll

rolled to different cross sections in the same grooves in the cogging mill, but this is because the position of the screwing-down gear is altered.

The cross sections of the ingot in each pass with the reversing cogging mills were determined from the position of the top roll. A special pointer was fixed to the top roll, which indicated the position of this roll on a vertical scale provided for the purpose. The length of ingot or bar was calculated from its cross section and weight. The crop ends were frequently cut off by bloom shears after the roughing passes, in which case a corresponding allowance was made in the calculations for the finishing passes.

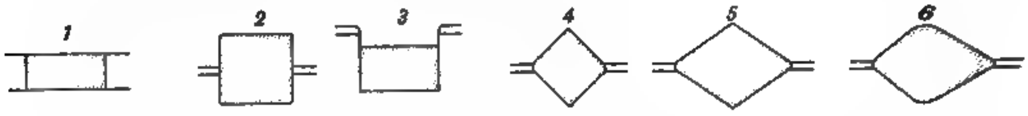


FIG. 335. — Sections in which only "Direct Pressure" occurs in the Process of Rolling. (Puppe.)

The elongation was calculated from the cross sections and the lengths, such calculations often being based on the cross section after the second or third pass, in order to obtain greater accuracy, as already mentioned. The "volume displaced" is obtained by multiplying the reduction in cross section by the length of the billet before the pass in question, i.e., $(Q_1 - Q_2) \times L_{q_1}$, where Q_1 = the cross section of the ingot or billet before the pass, Q_2 = the cross section after the pass, and L_{q_1} = length of billet before the pass.

In rolling there are two means by which the pressure is applied to the bar, viz., "direct" and "indirect" pressure. By direct pressure" is meant pressure which exists between the surfaces of two rolls, as, for example, with rolls grooved as shown in Fig 335.

The term ' indirect pressure" will be used to denote the pressure usually existing between the groove sides of one and the same roll, which produces principally a reduction in a horizontal direction (width) and not in a vertical direction (height), as is the case with the sections shown in Fig. 335. The following example will make this clear:

FIG. 336. — Illustration of "Indirect Pressure." (Puppe.)

If the flange of a rail (Fig. 336) be pressed in such a manner that its thickness a–b and a'–b' is reduced, then this must be due to indirect pressure along the whole line from c to d and c' to d'. It will be noticed that indirect pressure

takes place here both between the sides of the groove of the same roll as also between the two rolls.

Where the particles move solely in an axial direction along the bar, the energy required to accomplish this displacement is directly proportional to the product $(Q_1 - Q_2) \times L_{q_1}$, in which Q_1 and Q_2 represent the cross sections of two consecutive passes, and L_{q_1} the length of bar corresponding to the cross section Q_1. For shortness, we will denote this product, which represents the volume displaced, by V. The fraction $\frac{(Q_1 - Q_2) \times L_{q_1} \text{ (in cu. mm.)}}{\text{work done in rolling (in m. kg.)}}$ depends on the plasticity of the material, and, therefore, to a large extent on the temperature. By plotting a curve with the above fraction calculated for each pass as ordinates, and the corresponding temperatures as abscissæ, we can obtain from this the number of cubic millimeters of material which will be displaced per m. kg. at various temperatures.

Let us now investigate the case in which the particles of the metal do not move mainly in an axial direction along the bar, but also at right angles thereto. A simple example is that of a bar which is flattened out by rolls having no grooves to restrict the movement sideways.

The angle of incision into the bar should be such as not to cause excessive spreading. Incisions at acute angles naturally cause greater spreading than incisions at obtuse angles, but very often the proper form at the first passes can only be obtained by incision of the bar at an angle from about 40° to 60°,* in which case a considerable amount of lateral spreading cannot be avoided. It is then advisable to facilitate lateral spreading and not to hinder the movement too much by the sides of the grooves.

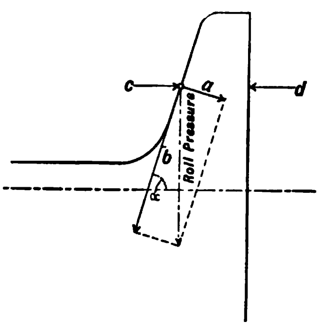


FIG. 337. — Effect of Inclination of Inner Surface of the Rail Flange on Energy required in Rolling. (Puppe.)

When designing rolls, successive profiles should be arranged in such a way as to obtain a smooth curve for V/E free from such sudden jumps as occur, for instance, in the curves in Fig. 332. It need hardly be said that the rolling of simple sections, such as flats, squares, rounds, etc., requires less power than the more complicated rail sections in which the flow of the metal is brought about by indirect pressure, and where the loss due to friction against the sides of the grooves is great. This loss should, of course, be kept as low as possible, and equally dis-

* Bartholme, Stahl und Eisen, 1907, p. 58.

tributed amongst the various passes. It can be reduced to a minimum by making the angle ∞ (Fig. 337) as small as possible, so as to obtain a large component a.

From the point of view of economy in energy consumption when rolling rails, it is very desirable that the inner surfaces of their flanges be inclined as much as possible. If, however, the inclination of the inner surfaces, or the thickness of the finished flange, has been fixed, the amount of indirect pressure required for the formation of the flange can be reduced to a minimum by working it as thin as possible at the first forming pass.

To sum up, the power required for complicated sections is greater than for simpler sections of the same final cross-sectional area, but this extra power depends to a very large extent on the skill with which the rolls are designed. If the rolls have the most favorable shape, the values for V/E for the various passes will be consistent with one another.

Plate XXXII contains curves which are calculated from the tests. The shaded areas represent the energy supplied by the motors to the mill, and cover, therefore, not only the work required for actual rolling, but also the power required for running the mill light and for accelerating. The power taken by the cogging mill generally increases towards the end of the pass, owing to the acceleration of the rotating masses and the increase in the no-lead losses.

The same holds good for a few of the roughing and finishing passes. At the last passes, however, the power taken decreases when the maximum speed has been attained, and the rotating masses are no longer accelerated. The peaks at the beginning of the curves for the last passes are due to this cause. The relatively high peak in the lower curve for pass No. 23 may be explained by the fact that maximum speed was reached in a very short time, as indicated by the sharp rise in the speed curve.

The speed curve (Plate XXXII) usually drops rapidly when the ingot enters the rolls, and sometimes it even falls to zero, and then rises again. Frequently the speed increases suddenly at the end of the pass, especially in cogging mills. These irregularities in speed are due to careless manipulation of the driver's lever. In reversing mills the kinetic energy of the rotating masses is seldom used to assist the motor, but it does happen occasionally.

From the acceleration curve (Fig. 338), it will be seen that a very large amount of energy is required to accelerate the rotating masses of a reversing mill; for instance, about 5300 h.p.-minutes are required to bring the rotating masses of this reversing mill up to a speed of 120 r.p.m. Assuming that the average speed is only 80 r.p.m., and that there are 20 passes, this means that

48,000 h.p.-minutes are expended in accelerating the rotating masses per ingot. This is a large percentage of the total energy required for rolling. It must be noted, however, that in the case of electrically driven reversing mills the energy expended in accelerating the rotating masses is largely returned again in the form of electric energy when the speed decreases, so that the net amount of energy required for acceleration purposes is not considerable. Where reversing

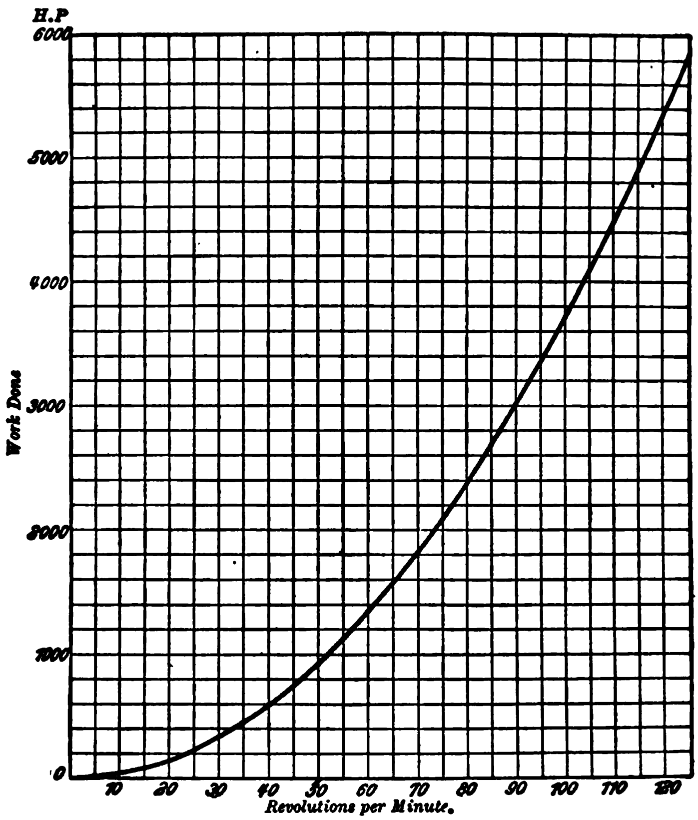


FIG. 338. — Work done in Accelerating the Rotating Masses in Reversing Mill. (Puppe.)

steam engines are employed, however, the work done in accelerating the rotating masses is lost, and this should be borne in mind when deciding whether for a given mill a reversible engine or a flywheel engine is best.

Rails after becoming so worn in the track as to be unfit for further service may be rerolled into new sections. A considerable tonnage of such rails has been rerolled by the McKenna process at a cost of about $7.00 per ton. The advantages claimed for this process are:

First. That the worn rail is selected material, as the imperfect rails have been eliminated to a large extent during the time the rails have been in service.

Second. The rerolling puts additional mechanical work upon the material, which should improve its quality.

The practical difficulties in connection with the process may be summarized as follows:

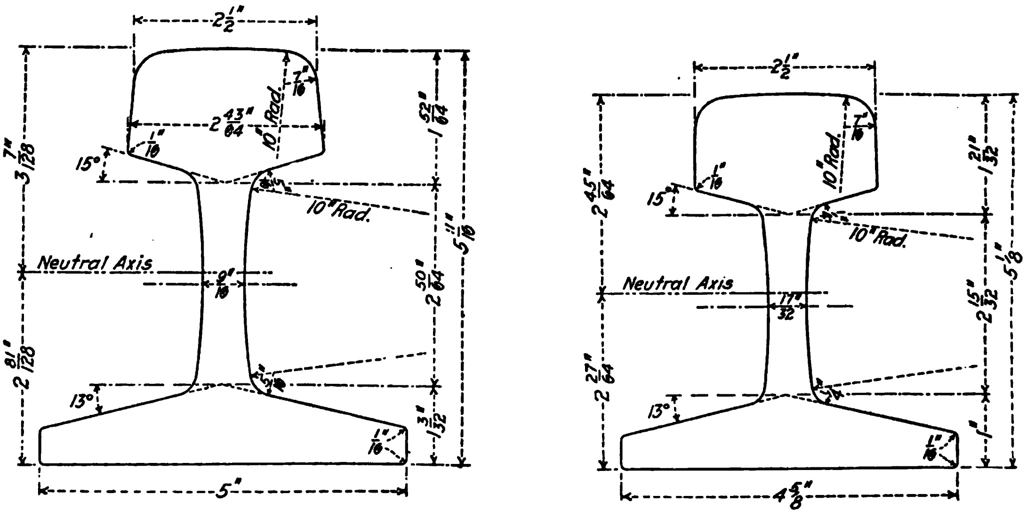
First. The rail must not be worn beyond a certain degree, as there must remain in the head of the rail a sufficient amount of metal to form the new head. The metal from the base and flange cannot be made to flow into the head to make up for its worn condition. In general it is not desirable to remove rails from the main track, which show only the amount of wear best adapted to rerolling; however, when it is necessary to remove rails from some cause other than reduction of section on account of wear it may prove economical to reroll them into sections of lesser weight.

Second. It is desirable that the rerolled rails may conform to standards already in use. This seems to be in a practical way difficult to accomplish, owing to the varying shape of the head of the rerolled rail, as the rail is much or little worn.

The following figures are taken from a record of a mile of 80-pound rail rerolled by the American McKenna Process Company.

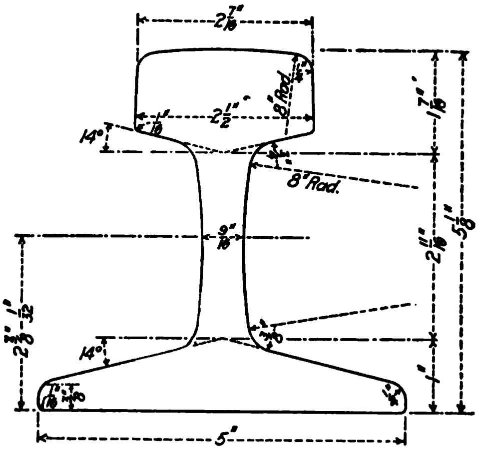
	Tons.
10,560 ft. of rail taken out of track	
Weight when new	125.71
Loss in track after 10 years' use	5.33
Weight sent to mill	120.38
10,151 ft. of rail received from mill	103.20
Scrap received from mill	17.18

The sections given in Fig. 339 and Plates VII and VIII of the rails used

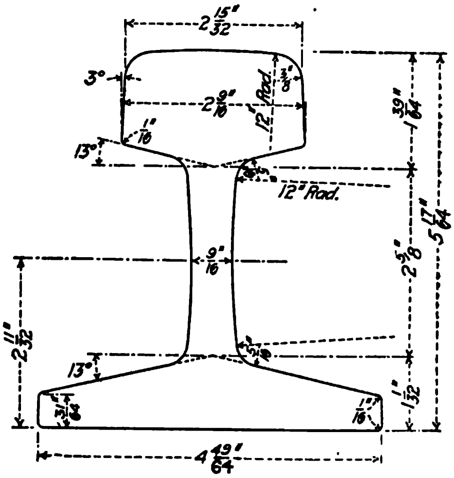


Pennsylvania, 100-lb. **Pennsylvania, 85-lb.**

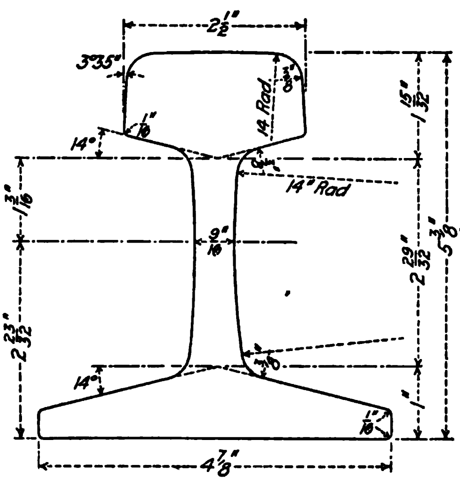
FIG. 339. — Recent Rail Sections. (Railroad Age Gazette.)



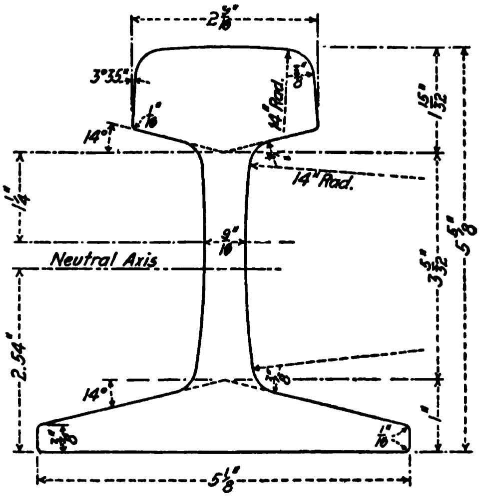
Canadian Pacific, 85-lb.



Baltimore & Ohio, 90-lb.



Santa Fe, 85-lb.



Burlington, 90-lb.

Section.	Area of			
	Head,	Web,	Base,	Total,
	per cent.	per cent.	per cent.	per cent.
Pennsylvania, 100-lb.	41.0	18.6	40.4	100.0
Pennsylvania, 85-lb.	42.2	17.8	40.0	100.0
Canadian Pacific, 85-lb.	36.8	22.2	41.0	100.0
Santa Fe, 85-lb.	37.0	22.8	40.2	100.0
Burlington, 90-lb.	36.2	24.0	39.8	100.0

FIG. 339 (continued). — Recent Rail Sections. (Railroad Age Gazette.)

at the present time show clearly the willingness on the part of the railroads to meet the criticism of the manufacturers in regard to the faults in the design of the heavier A. S. C. E. sections.

These new thick-base sections, adopted after the studies of 1907, cool with less curvature than the former thin-base types and require less cold-straightening. There appears to have been a material reduction in the number of base failures in the new sections as compared with the A. S. C. E. design.

A number of students of this subject think that there is room for still further improvements along this line to eliminate to an even greater extent the failures in the base of the rail. This is evidenced by the new Chicago and North-Western section for 100-pound rail in which the base is $\frac{35}{64}$ inch thick at the outer edge. Dr. P. H. Dudley has designed a new section giving to the fillet between the base and the web a radius of 1 inch. The Illinois Steel Company at its South Works plant is also experimenting with a new section of 110 pounds in weight which is similar to that used on the foreign railways in that the upper surface of the base is broken at two angles.

CHAPTER VII

RAIL SPECIFICATIONS

34. Comparison of American Specifications

The rail committee of the American Railway Engineering and Maintenance of Way Association revised their specifications in the latter part of the year 1909; these were subsequently withdrawn and in March, 1912, the committee presented to the American Railway Engineering Association, which was now the name of the association, specifications for carbon steel rails.

Some paragraphs, such as those relating to carbon under remarks in Table XCIX and Nos. 14 and 15, relating to physical requirements, were not considered as final, it being thought that the committee did not have sufficient information in its possession to make these sections in the specifications mandatory. The requirements in section 14 for ductility were somewhat lower than some of the members thought desirable. Paragraph No. 15, referring to deflections as a method of classifying rails, is also tentative, and it is the intention, when sufficient data is at hand, to prescribe maximum and minimum limits for deflections under the drop test. The committee will continue its investigations and the specifications in these respects will be subject to change.

On January 10, 1912, the Pennsylvania revised its specifications for Bessemer and open-hearth rails.

On January 1, 1909, the Association of American Steel Manufacturers issued standard specifications for Bessemer and open-hearth rails. These rail specifications, adopted by the steel manufacturers of the United States and Canada, which are practically the same for the different companies, indicate the views of the rail makers as to the proper tests and chemical composition for securing good rails. The A. S. C. E. sections are still officially regarded as standard practice.

Standard specifications for Bessemer and open-hearth steel rails were adopted by letter ballot on August 16 1909, by the American Society for Testing Materials.

In October, 1909, the Harriman Lines adopted standard specifications for Bessemer and open-hearth steel rails; the open-hearth specifications were subsequently revised in February, 1910.

The above specifications show the development during recent years of rail specifications in this country and an examination of their requirements will prove of interest. The American Railway Engineering Association specifications of 1912 reflect the latest thought and are noticeable for the increase in the number of physical tests over those required in earlier specifications. A great many defects, such as piping of the ingot, can be adequately guarded against by proper physical tests, and in general it would appear desirable to leave the producer free in such cases to adopt his own methods of manufacture. Within certain limits, however, the specifications may well be drawn to exclude practice which is known to result in defective material. The desirability of doing this is emphasized by the great difference in quality found in rollings from different mills and in some cases for rails from the same mill, but rolled in different years. The specifications given in Article 35 are a good example of specifications drawn with a view to eliminating defective practice at the mill.

The trend of recent specifications is to increase the amount of inspection which is being given the rail at the mills. The plan of the R. W. Hunt and Company of placing inspectors throughout the mill to watch the entire process of manufacture is evidence of this.

Inspection

Am. Ry. Eng. Assn.:

1. Inspectors representing the purchaser have free entry to the works of the manufacturer at all times while the contract is being executed, and shall have all reasonable facilities afforded them by the manufacturer to satisfy them that the rails have been made in accordance with the terms of the specifications.

2. All tests and inspections shall be made at the place of manufacture, prior to shipment, and shall be so conducted as not to interfere unnecessarily with the operation of the mill.

All of the specifications are substantially the same as the above.

Material

Am. Ry. Eng. Assn.:

3. The material shall be steel made by the Bessemer or open-hearth process provided by the contract.

The clause in reference to material in the Pennsylvania Specification is the same, but in the other specifications it is omitted and a separate specification written for each class of material, i.e., Bessemer or open-hearth steel.

Chemical Requirements

Am. Ry. Eng. Assn.:

4. The chemical composition of the steel from which the rails are rolled, determined as prescribed in Section 7, shall be within the following limits: (See Table XCIX.)

Table XCIX presents a comparison of the chemical requirements of the different specifications.

The Committee on Standard Rail and Wheel Sections of the American Railway Association, in its report of March 23, 1908, to the association, stated: "In the matter of chemistry specifications for Bessemer steel rail, statistics were obtained from the officers of the Ore Producers' Association which convinced the committee that it would be impossible for the mills to furnish more than a small percentage of the total rail requirements of the railways with a phosphorus specification less than .10.

"The optional specification for .085 phosphorus prepared by the joint committee of manufacturers and railway men is now in the hands of all members, and is, therefore, available for use by those who are able to obtain low-phosphorus Bessemer rails. It is not considered proper, however, to require less than .10 phosphorus in a specification intended for general use. Members desiring to obtain a low-phosphorus rail will have the further option of using open-hearth steel.

The committee conferred with a number of disinterested experts on the phosphorus question, and among the principal authorities consulted were William Metcalf, of Pittsburg, Robert Forsyth, of Chicago, and Henry M. Howe, of Columbia University. These gentlemen all agreed that it would be unreasonable to require less than .10 phosphorus in a specification for Bessemer rails intended to cover purchases for all American railways."

The Pennsylvania specification for open-hearth rails makes the upper limits for classification A, phosphorus .03 and carbon .83; for classification B, .04 phosphorus and .75 carbon. The desired carbon for the two grades is .75 for the lower phosphorus, and .70 for the higher. The reason for making two classifications for open-hearth rails relates principally to the cost of manufacture. It was thought desirable to specify phosphorus as low as .03 so that high carbon could be used and the wearing quality of the rails, particularly on curves, would be materially improved. But the extra time required in the open-hearth furnace to reduce phosphorus from .04 to .03 results in some increase in the cost of manufacture, and a slight addition to the normal price per ton is added for the class A rails.

TABLE XCIX.—CHEMICAL COMPOSITION OF STANDARD AMERICAN SPECIFICATIONS

Composition. Bessemer.

Specification.	Date.	Weight of Rail, Lbs.	Carbon. Min.	Carbon. Des'd.	Carbon. Max.	Manganese. Min.	Manganese. Max.	Silicon. Min.	Silicon. Max.	Phosphorus. Min.	Phosphorus. Max.	Sulphur. Min.	Sulphur. Max.
Am. Ry. Eng. Assn.	1912	70 and over but under 85 85–100	0.40 0.45		0.50 0.55	0.80	1.10	.	0.20	.	0.10	...	...
Ass. of Amer. Steel Mfgrs.	1909	50–60 61–70 71–80 81–90 91–100	0.35 0.40 0.43 0.45		0.45 0.50 0.5[illegible] 0.5[illegible]	0.70 0.75 0.80 0.84	1.00 1.05 1.10 1.14		0.20		0.10	..	
American Society for Testing Materials.	1909	...	.	..	..	...	..	...	....	..	....	....	....
Pennsylvania.	1912	85–100	0.45	0.50	0.55	0.80	1.20	0.05	0.20	.	0.10	.	.....
Harriman Lines.	1909 1910	65 75 90	0.40 0.45 0.55	.. ..	0.50 0.55 0.65	0.80	1.05	......	0.20	...	0.085	....	...

Composition. ·hearth.

Specification.						Silicon. Min.	Silicon. Max.	Phosphorus. Min.	Phosphorus. Max.	Sulphur. Min.	Sulphur. Max.	Remarks.
Am. Ry. Eng. Assn.						..	0.20	.	0.04	...	.	*Modification of Carbon for Low Phosphorus.*—When the material used at any mill is such that the average phosphorus content of the ingot metal used in the Bessemer process is running below 0.08 and in the Open-hearth process is running below 0.03, and if it seems mutually desirable, the carbon may be increased at the rate of 0.035 for each 0.01 that the phosphorus content of the ingot metal used averages below 0.08 for Bessemer steel, or 0.03 for Open-hearth steel. *Average Carbon.*—It is desired that the percentage of carbon in an entire order of rails shall average as high as the mean percentage between the upper and lower limits specified.
Ass. of Amer. Steel Mfgrs.	0.46 0.52 0.59 0.62	.	0.59 0.65 0.72 0.75	0.60	0.90	.	0.20		0.04	.	..	
American Society for Testing Materials.	..	..	..	....	..	...	.	..	.	...	.	Same as Manufacturers', except that in the open-hearth specifications "for each decrease of 0.003 per cent in phosphorus down to 0.03 per cent phosphorus, an increase of 0.01 per cent carbon will be accepted."
Pennsylvania.	0.70 0.62	0.75 0.70	0.83 0.75	.	0.80	0.05	0.20	..	0.03 0.04	.	.	Classification "A" for open-hearth rails. Classification "B" for open-hearth rails.
Harriman Lines.	0.50 0.55 0.63	.. . .	0.62 0.68 0.78	0.70	1.00		0.20	..	0.04	.		Where mills cannot furnish steel rail with a phosphorus content less than 0.10 per cent carbon shall be as follows: 65 lb. .38–.48 % 75 lb. .42–.52 % 90 lb. .50–.60 %

Sulphur is not generally mentioned in the chemical requirements, but the trend of modern specifications is to require that this element be reported. This is illustrated by the American Railway Engineering Association specification for analyses given below.

Analyses

Am. Ry. Eng. Assn.:

7. In order to ascertain whether the chemical composition is in accordance with the requirements, analyses shall be furnished as follows:

(*a*) For Bessemer process the manufacturer shall furnish to the inspector, daily, carbon determinations for each heat before the rails are shipped, and two chemical analyses every twenty-four hours representing the average of the elements, carbon, manganese, silicon, phosphorus, and sulphur contained in the steel, one for each day and night turn respectively. These analyses shall be made on drillings taken from the ladle test ingot not less than one-eighth inch beneath the surface.

(*b*) For Open-hearth process, the makers shall furnish the inspectors with a chemical analysis of the elements, carbon, manganese, silicon, phosphorus, and sulphur, for each heat.

(*c*) On request of the inspector, the manufacturer shall furnish drillings from the test ingot for check analyses.

The Pennsylvania specifications are the same as the above. The other specifications only require one complete chemical analysis every twenty-four hours in the Bessemer process. The manufacturers and American Society for Testing Materials require that the analyses shall be made on drillings taken not less than one-fourth inch beneath the surface of the test ingot. The Harriman Lines specification does not give the depth at which the drillings should be taken.

Physical Requirements

Table C compares the physical requirements of the different specifications.

Am. Ry. Eng. Assn.:

Physical Qualities.

8. Tests shall be made to determine:
(*a*) Ductility or toughness as opposed to brittleness.
(*b*) Soundness.

Method of Testing.

9. The physical qualities shall be determined by the Drop Test.

Drop Testing Machine.

10. The drop-testing machine used shall be the standard of the American Railway Engineering Association.

(*a*) The tup shall weigh 2000 pounds, and have a striking face with a radius of five inches.
(*b*) The anvil block shall weigh 20,000 pounds, and be supported on springs.
(*c*) The supports for the test pieces shall be spaced 3 feet between centers and shall be a part of, and firmly secured to the anvil. The bearing surfaces of the supports shall have a radius of 5 inches.

Pieces for Drop Test.

11. Drop tests shall be made on pieces of rail not less than 4 feet and not more than 6 feet long. These test pieces shall be cut from the top end of the top rail of the ingot, and marked on the base or head with gage marks 1 inch apart for 3 inches each side of the center of the test piece, for measuring the ductility of the metal.

Temperature of Test Pieces.

12. The temperature of the test pieces shall be between 60 and 100 degrees Fahrenheit.

Height of Drop.

13. The test piece shall, at the option of the inspector, be placed head or base upwards on the supports, and be subjected to impact of the tup falling free from the following heights:

For 70-pound rail	16 feet
For 80-, 85-, and 90-pound rail	17 feet
For 100-pound rail	18 feet

Elongation or Ductility.

14. Under these impacts the rail under one or more blows shall show at least 6 per cent elongation for 1 inch or 5 per cent each for two consecutive inches of the 6-inch scale, marked as described in Section 11.

Permanent Set.

15. It is desired that the permanent set after one blow under the drop test shall not exceed that in the following table, and a record shall be made of this information.

Rail.			Permanent Set, measured by Middle Ordinate in Inches in a Length of 3 ft.	
Section.	Weight per Yard.	Moment of Inertia.	Bessemer Process.	O. H. Process.
A.R.A.-A	100	48.94	1.65	1.45
A.R.A.-B	100	41.30	2.05	1.80
A.R.A.-A	90	38.70	1.90	1.65
A.R.A.-B	90	32.30	2.20	2.00
A.R.A.-A	80	28.80	2.85	2.45
A.R.A.-B	80	25.00	3.15	2.85
A.R.A.-A	70	21.05	3.50	3.10
A.R.A.-B	70	18.60	3.85	3.50

Test to Destruction.

16. The test pieces which do not break under the first or subsequent blows shall be nicked and broken to determine whether the interior metal is sound.

Bessemer Process Drop Tests.

17. One piece shall be tested from each heat of Bessemer steel.

(*a*) If the test piece does not break at the first blow and shows the required elongation (Section 14), all of the rails of the heat shall be accepted, provided that the test piece when nicked and broken does not show interior defect.

(*b*) If the piece breaks at the first blow, or does not show the required elongation (Section 14), or if the test piece shows the required elongation, but when nicked and broken shows interior defect, all of the top rails from that heat shall be rejected.

(*c*) A second test shall then be made of a test piece selected by the inspector from the top end of any second rail of the same heat, preferably of the same ingot. If the test piece does not break at the first blow, and shows the required elongation (Section 14), all of the remainder of the rails of the heat shall be accepted, provided that the test piece when nicked and broken does not show interior defect.

(*d*) If the piece breaks at the first blow, or does not show the required elongation (Section 14), or if the piece shows the required elongation, but when nicked and broken shows interior defect, all of the second rails from that heat shall be rejected.

(*e*) A third test shall then be made of a test piece selected by the inspector from the top end of any third rail of the same heat, preferably of the same ingot. If the test piece does not break at the first blow and shows the required elongation (Section 14), all of the remainder of the rails of the heat shall be accepted, provided that the test piece when nicked and broken does not show interior defect.

(*f*) If the piece breaks at the first blow, or does not show the required elongation (Section 14), or if the piece shows the required elongation, but when nicked and broken shows interior defect, all of the remainder of the rails from that heat shall be rejected.

Open-hearth Process Drop Tests.

18. Test pieces shall be selected from the second, middle, and last full ingot of each open-hearth heat.

(*a*) If two of these test pieces do not break at the first blow and show the required elongation (Section 14), all of the rails of the heat shall be accepted, provided that these test pieces when nicked and broken do not show interior defect.

(*b*) If two of the test pieces break at the first blow, or do not show the required elongation, or if any of the pieces that have been tested under the drop when nicked and broken show interior defect, all of the top rails from that heat shall be rejected.

(*c*) Second tests shall then be made from three test pieces selected by the inspector from the top end of any second rails of the same heat, preferably of the same ingots. If two of these test pieces do not break at the first blow and show the required elongation (Section 14), all of the remainder of the rails of the heat shall be accepted, provided that the pieces that have been tested under the drop when nicked and broken do not show interior defect.

(*d*) If two of these test pieces break at the first blow or do not show the required elongation (Section 14), or if any of the pieces that have been tested under the drop when nicked and broken show interior defect, all of the second rails of the heat shall be rejected.

(*e*) Third tests shall then be made from three test pieces selected by the inspector from the top end of any third rails of the same heat, preferably of the same ingots. If two of these test pieces do not break at the first blow, and show the required elongation (Section 14), all of the remainder of the rails of the heat shall be accepted, provided that the pieces that have been tested under the drop when nicked and broken do not show interior defect.

(*f*) If two of these test pieces break at the first blow or do not show the required elongation (Section 14), or if any of the pieces, that have been tested under the drop when nicked and broken show interior defect, all of the remainder of the rails from that heat shall be rejected.

The drop-testing machine has been standardized, and it is claimed that the lower drop called for under the new conditions is equivalent to the higher drop of 22 feet previously specified.

The provision in the American Railway Engineering Association and Pennsylvania specifications that drop testing shall be continued to the destruction of the specimen is a precaution which should result in a material benefit to the railway by reducing the number of piped rails, which, in spite of the usual inspection and tests, get into the main track. It seems far more desirable not to specify any definite discard, but to test to destruction a number of rail butts representing a certain proportion of the total output, and to base rejections on the results of these tests.

The Cambria Steel Company rolled a considerable tonnage of rails under these specifications, and the testing to destruction unquestionably detected the pipes. To find to what depth the pipes extended, they polished the ends of the drop-test pieces and cut the top rail adjoining the test pieces into small lengths, examining carefully each cut for pipes.. It was found that of the heats showing pipes in the drop-test piece when tested to destruction, sixty per cent contained pipes so short that they were confined entirely to the crop end. Of the remaining forty per cent which extended into the top rail, nearly half showed a pipe extending less than four feet.

Most of the specifications require that two test pieces be tested in the open-hearth process but only one in the Bessemer process. This is because of the greater tonnage of metal in an open-hearth heat as compared to a Bessemer heat, there being about five times as much metal. All the basic open-hearth rail steel now

TABLE C.—PHYSICAL REQUIREMENTS OF STANDARD AMERICAN SPECIFICATIONS.

		Association of American Steel Manufacturers (1909) and American Society for Testing Materials (1909).	Harriman Lines, Bessemer Steel Rails, 1909, open-hearth Steel Rails, 1910.
9 The physical qualities shall be determined by the Drop Test	Same as Am. Ry. Eng. Assn.		
Drop Testing Machine: 10 The drop-testing machine used shall be the standard of the American Railway Engineering Association. (a) The tup shall weigh 2000 pounds, and have a striking face with a radius of five inches. (b) The anvil block shall weigh 20,000 pounds, and be supported on springs. (c) The supports for the test pieces shall be spaced 3 feet between centers and shall be a part of and firmly secured to the anvil. The bearing surfaces of the supports shall have a radius of 5 inches.	Same as Am. Ry. Eng. Assn.	The drop-testing machine shall have a tup of 2000 pounds weight, the striking face of which shall have a radius of not more than 5 inches, and the test rail up- s 3 ock 000 rts nly secured to the anvil.	Same as manufacturers'.
Pieces for Drop Test: 11. Drop tests shall be made on pieces of rail not less than 4 feet and not more than 6 feet long. These test pieces shall be cut from the top end of the top rail of the ingot, and marked on the base or head with gage marks 1 inch apart for 3 inches each side of the center of the test piece, for measuring the ductility of the metal.	No provision made for measuring the ductility, otherwise the same as Am. Ry. Eng. Assn.	Drop tests may be made on pieces of rail not less than 4 feet and not more than 6 feet long.	Same as Pennsylvania.
Temperature of Test Pieces: 12. The temperature of the test pieces shall be between 60 and 100 degrees Fahrenheit.	Between 60 and 120 degrees.	Between 60 and 120 degrees.	
Height of Drop. 13. The test piece shall, at the option of the inspector, be placed head or base upwards on the supports, and be subjected to impact of the tup falling free from the following heights: For 70-pound rail .... 16 feet For 80-, 85-, and 90-pound rail .... 17 feet For 100-pound rail .... 18 feet	For 85-pound rail .... 15 feet For 100-pound rail .... 15 feet	Lbs. / Lbs. / Ft. 50 up to and inc. 60 15 61 up to and inc. 70 16 71 up to and inc. 80 16 81 up to and inc. 90 17 91 up to and inc. 100 18	For 65-pound rail..15 feet For 75-pound rail 16 feet For 90-pound rail..17 feet
Elongation or Ductility: 14. Under these impacts the rail under one or more blows shall show at least 6 per cent elongation for 1 inch or 5 per cent each for two consecutive inches of the 6-inch scale, marked as described in Section 11.			
Permanent Set: 15. It is desired that the permanent set after one blow under the drop test shall not exceed that in the following table, and a record shall be made of this information. (See table below.)	The deflection for No. 1 classification rails must not exceed that indicated by a middle ordinate of 2 inches in 3 feet for 100-pound section, and 2½ inches for 85-pound section.		
Test to Destruction: 16 The test pieces which do not break under the first or subsequent blows shall be nicked and broken to determine whether the interior metal is sound	Same as Am. Ry. Eng. Assn.		

Rail.			Permanent Set, measured by Middle Ordinate in Inches in a Length of 3 ft.	
Section.	Weight per Yard.	Moment of Inertia.	Bessemer Process.	O. H. Process.
A.R.A.-A.	100	48 94	1 65	1 45
A.R.A.-B.	100	41 30	2 05	1 80
A.R.A.-A.	90	38 70	1 90	1 65
A.R.A.-B.	90	32 30	2 20	2 00
A.R.A.-A.	80	28 80	2 65	2 45
A.R.A.-B.	80	25 00	3.15	2 85
A.R.A.-A.	70	21 05	3 50	3 10
A.R.A.-B.	70	18 60	3 85	3 60

Same as manufacturers'.	Three test pieces shall be selected from each melt at approximately	the other requirements of these specifications. Should the third test fail, all the rails from the melt shall be rejected.

being made in the United States is melted in furnaces of a minimum capacity of 40 tons, and the majority of it is made in 50-ton or 80-ton furnaces.

The feeling is growing among railway engineers that present specifications do not go far enough in specifying tests of a certain number of ingots from each heat, but that specimens should be tested from each individual ingot. On account of the uncertainty attending the formation of the pipe in the ingot an increase in the number of tests per heat would appear desirable.

The Pennsylvania is the only specification that provides for a limiting deflection, although the American Railway Engineering Association give limits that it is desired not to exceed and state that it is proposed to prescribe the requirements in regard to deflection as soon as proper limits have been decided on. In the absence of a tension test it would seem desirable to make provisions for fixing maximum and minimum limits for the deflection.

The American Railway Engineering Association specifications are the only specifications which call for a ductility test. This test has been used for some time by Dr. P. H. Dudley, as shown in the New York Central Lines specifications given in Article 35.

No. 1 *and No.* 2 *Rails*

Am. Ry. Eng. Assn.:

19. No. 1 classification rails shall be free from injurious defects and flaws of all kinds.

20. (*a*) Rails which, by reason of surface imperfections, or for causes mentioned in Section 30 hereof, are not classed as No. 1 rails will be accepted as No. 2 rails, but No. 2 rails which contain imperfections in such number or of such character as will, in the judgment of the inspector, render them unfit for recognized No. 2 uses will not be accepted for shipment.

(*b*) No. 2 rails to the extent of 5 per cent of the whole order will be received. All rails accepted as No. 2 rails shall have the ends painted white and shall have two prick punch marks on the side of the web near the heat number near the end of the rail, so placed as not to be covered by the splice bars.

All of the specifications state that "No. 1 rails shall be free from injurious defects and flaws of all kinds."

The Pennsylvania specifications for No. 2 rails are the same as the above with the clause added that rails which exceed the prescribed limits of deflection in the drop test may be accepted as No. 2 rails. The manufacturers' specifications are somewhat different and are given below.

Rails which, by reason of surface imperfections, are not classed as No. 1 rails

shall be considered No. 2 rails, but No. 2 rails shall not be accepted for shipment which have flaws in the head of more than $\frac{1}{4}$ inch, or in the flange of more than $\frac{1}{2}$ inch in depth, and these shall not, in the judgment of the inspector, be, in any individual rail, so numerous or of such a character as to render it unfit for recognized No. 2 rail uses. Both ends of No. 2 rails shall be painted white.

The Harriman Lines specifications are the same as the manufacturers' with the additional clauses that No. 2 rails will be accepted up to 5 per cent of the whole order, and in common with the American Society for Testing Materials they will not accept rails as No. 2 from heats which failed under the drop test.

Quality of Manufacture

Am. Ry. Eng. Assn.:

21. The entire process of manufacture shall be in accordance with the best current state of the art.

This section is common to all specifications except the manufacturers'.

Bled Ingots

Am. Ry. Eng. Assn.:

22. Bled ingots shall not be used.

This is specified by all except the manufacturers', with an additional clause providing that the ingots be kept in a vertical position until ready to be rolled, or until the metal in the interior has had time to solidify.

Discard

Am. Ry. Eng. Assn.:

23. There shall be sheared from end of the bloom formed from the top of the ingot, sufficient metal to secure sound rails.

The Pennsylvania requirements are the same as the American Railway Engineering Association, while the Manufacturers' specifications do not refer to this part of the process.

The American Society for Testing Materials and the Harriman Lines specifications call for a definite discard as follows:

A. S. for T. M.:

There shall be sheared from the end of the blooms formed from the top of the ingots not less than x per cent,* and if, from any cause, the steel does not then appear to be solid, the shearing shall continue until it does.

* The percentage of minimum discard in any case to be subject to agreement, and it should be recognized that the higher this percentage the greater will be the cost.

Harriman Lines:

1. (*d*) There shall be sheared from the end of the bloom and rail formed from the top of the ingot a total discard of not less than nine (9) per cent of the weight of the ingot, and if, from any cause, the steel does not then appear to be solid, the shearing shall continue until it does. If, by the use of any improvements in the process of making ingots, the defects known as "piping" shall be prevented, the above shearing requirements may be modified.

On this system, by excluding the top, or A, rails from main-line use, the effect of an additional 30 per cent discard is obtained, and at the same time the discard is saved for use on sidings and other locations where second-hand rails usually are used; the road thus doing its own discarding beyond the manufacturers' allowance, and saving the product without risk to the quality of the main-track rails.

In view of the uncertainties, as to the length of the pipe it appears that the position taken by the American Railway Engineering Association and the Pennsylvania System in their specifications is the most reasonable one, viz., to leave the discard to the manufacturers, and to safeguard the product by proper tests, especially by choosing the test piece from such a location, and making the rejections such, that it will be to the interest of the manufacturer to voluntarily discard the metal which will not stand test.

Length

Am. Ry. Eng. Assn.:

24. The standard length of rails shall be 33 feet, at a temperature of 60 degrees Fahrenheit. Ten per cent of the entire order will be accepted in shorter lengths varying by 1 foot from 32 feet to 25 feet. A variation of $\frac{1}{4}$ inch from the specified lengths will be allowed. No. 1 rails less than 33 feet long shall be painted green on both ends.

TABLE CI.—LENGTH OF RAILS IN STANDARD AMERICAN SPECIFICATIONS

Specifications.	Standard Lengths.	Shorter Lengths that will be Accepted.
	Feet.	Feet.
Am. Ry. Eng. Assn.	33*	32, 31, 30, 29 28, 27, 26, 25
Manufacturers'	30 or 33	Varying by even feet to twenty-four (24) feet.
A. S. for T. M.	30 or 33	
Harriman Lines	33	
Pennsylvania	33*	30, 27½, 25

* At a temperature of 60° F.

All of the specifications agree in allowing ten per cent of the entire order to be shorter lengths than the standard and permit of a variation of $\frac{1}{4}$ inch in length from that specified. All call for the short-length rails to be painted green on both

ends. The standard length and short lengths that will be accepted, however, vary, and the requirements given in the various specifications are shown in Table CI.

Shrinkage or Control of Finishing Temperature

Am. Ry. Eng. Assn.:

25. The number of passes and speed of train shall be so regulated that, on leaving the rolls at the final pass, the temperature of the rail will not exceed that which requires a shrinkage allowance at the hot saws, for a rail 33 feet in length and of 100 pounds' section, of $6\frac{3}{4}$ inches, and $\frac{1}{8}$ inch less for each 10 pounds' decrease in section.

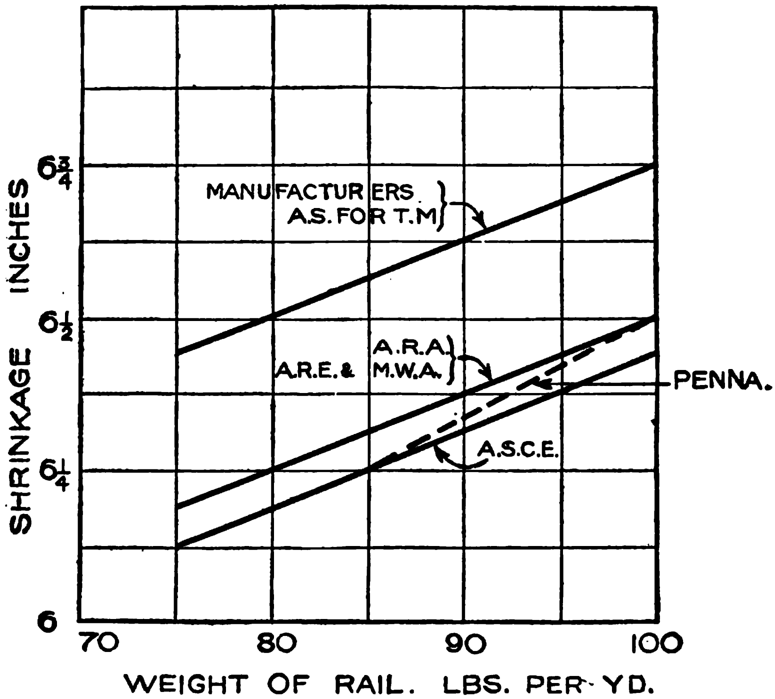


FIG. 340. — Shrinkage Allowed in American Specifications in 1909.

26. The bars shall not be held for the purpose of reducing their temperature, nor shall any artificial means of cooling them be used after they leave the finishing pass. Rails, while on the cooling beds, shall be protected from snow and water.

The other specifications are the same, except that in the Manufacturers' American Society for Testing Materials and Harriman Lines, the statement that rails, while on the cooling beds, shall be protected from snow and water, is omitted.

A greater shrinkage is allowed in present specifications than was formerly the case. Fig. 340 shows the allowance of different specifications in 1909; it will be

noted that the shrinkage has been increased to agree with the higher figure given by the manufacturers. In the Pennsylvania requirements of that date, it was provided that the shrinkage allowance be decreased at the rate of $\frac{1}{100}$ inch for each second of time elapsed between the rail leaving the finishing rolls and being sawed. The A. S. C. E. specifications called for $\frac{1}{90}$ inch in place of $\frac{1}{100}$ inch.

The control of the finishing temperature by the amount of contraction which the rail undergoes in cooling from the finishing to the atmospheric temperature appears to be the only method practical to use. Other efforts have been made to determine the finishing temperature by the use of pyrometers and by the examination of the microstructure of the rails. The use of pyrometers naturally suggested itself at first as the most promising means of accomplishing that purpose, but it was soon found that no pyrometric device existed which could be applied in a practical way to the detection of the temperature of quickly moving rails. The micro-test, although attractive and useful, can only be applied to a very small percentage of the rails manufactured, and this is its greatest weakness.

Section

Am. Ry. Eng. Assn.:

27. The section of rails shall conform as accurately as possible to the templet furnished by the railroad company. A variation in height of $\frac{1}{64}$ inch less or $\frac{1}{32}$ inch greater than the specified height and $\frac{1}{16}$ inch in width of flange will be permitted; but no variation shall be allowed in the dimensions affecting the fit of the splice bars.

The other specifications are substantially the same as those given above. The Manufacturers' specify A. S. C. E. sections; the Harriman Lines, A. R. A. section "A" 90-pound, Railroad Company's "Common Standard" 75-pound, A. S. C. E. section, 65-pound; and the American Society for Testing Materials say, unless otherwise specified, A. S. C. E. sections.

Weight

Am. Ry. Eng. Assn.:

28. The weight of the rails specified in the order shall be maintained as nearly as possible, after complying with the preceding section. A variation of one-half of one per cent from the calculated weight of section, as applied to an entire order, will be allowed.

29. Rails accepted will be paid for according to actual weights.

The other specifications are substantially the same as the above.

Straightening

Am. Ry. Eng. Assn.:

30. The hot straightening shall be carefully done, so that gagging under the cold presses will be reduced to a minimum. Any rail coming to the straightening presses showing sharp kinks or greater camber than that indicated by a middle ordinate of 4 inches in 33 feet, for A. R. A. type of sections, or 5 inches for A. S. C. E. type of sections, will be at once classed as a No. 2 rail. The distance between the supports of rails in the straightening presses shall not be less than 42 inches. The supports shall have flat surfaces and be out of wind.

All of the specifications are substantially the same.

Drilling

Am. Ry. Eng. Assn.:

31. Circular holes for joint bolts shall be drilled to conform accurately in every respect to the drawing and dimensions furnished by the Railroad Company.

Substantially the same for all specifications.

Finishing

32. (*a*) All rails shall be smooth on the heads, straight in line and surface, and without any twists, waves or kinks. They shall be sawed square at the ends, a variation of not more than one-thirty-second inch being allowed; and burrs shall be carefully removed.

(*b*) Rails improperly drilled or straightened, or from which the burrs have not been removed, shall be rejected, but may be accepted after being properly finished.

Substantially the same for all specifications.

Branding

Am. Ry. Eng. Assn.:

33. The name of the manufacturer, the weight and type of rail, and the month and year of manufacture shall be rolled in raised letters and figures on the side of the web. The number of the heat and a letter indicating the portion of the ingot from which the rail was made shall be plainly stamped on the web of each rail, where it will not be covered by the splice bars. The top rails shall be lettered "A," and the succeeding ones "B," "C," "D," etc., consecutively; but in case of a top discard of twenty or more per cent, the letter "A" will be omitted. Open-hearth rails shall be branded or stamped "O. H." All markings of rails shall be done so effectively that the marks may be read as long as the rails are in service.

The Pennsylvania specifications are the same as the above.

All of the other specifications omit the clause in the American Railway Engineering Association specifications in reference to omitting the letter "A" in case of a top discard of twenty per cent or more, but are substantially the same in other respects. The Harriman Lines specify that all "A" rails shall have the top of the flange at each end painted yellow, and the American Society for Testing Materials only require rails weighing 70 pounds per yard or over to be stamped with a letter to indicate the portion of the ingot from which the rail was rolled.

Separate Classes

Am. Ry. Eng. Assn.:

34. All classes of rails shall be kept separate from each other.

Loading

Am. Ry. Eng. Assn.:

35. All rails shall be loaded in the presence of the inspector.

The Pennsylvania specifications are the same for both of the above clauses. The Harriman Lines specifications contain the following clause:

The following classes of rail shall be loaded separately as far as practicable, excepting at the finishing of an order or the end of a rolling. In this case the different classes shall be kept separate by placing strips of wood between each class, and each shipping notice shall contain full information as to the contents of each car:

No. 1 rails, B, C, D, etc., full lengths.

No. 1 rails, B, C, D, etc., short lengths.

No. 1 "A" rails; that is, rails from the top of the ingot, full length.

No. 1 "A" rails, short length.

No. 2 rails, all lengths.

35. Specifications (New York Central Lines) for Basic Open-hearth Rails

1st — Chemical Composition:

	80 Lb.	90 Lb.	100 Lb.
Carbon	.55 to .68	.60 to .73	.62 to .75
Manganese	.70 to 1.00	.70 to 1.00	.70 to 1.00
Silicon	.10 to .20	.10 to .20	.10 to .20
Phos. not exceed	.04	.04	.04

To adjust the chemical composition to the special conditions of manufacture at each mill, the engineer representing the railroad company, from the inspection of the ingots, their heating, blooming, and rolling into rails, shall have the right to select the lower or average limit of either the silicon or man-

ganese, or both, with the average carbon content as the working basis for making the steel, as he may find requisite for good setting ingots with freedom from pipes and rolling into tough steel by the plant of the manufacturer.

2nd — Process of Manufacture: The entire process of manufacture and testing shall be in accordance with the best current state of the art, and special care shall be taken to conform to the following instructions:

(*a*) Excessive use of material thrown into the teeming ladle to set the stopper must be avoided.

(*b*) The steel must be well deoxidized and the waste products eliminated before the ingots are teemed.

(*c*) The steel must be made to set quiet by the chemical composition in the molds without the addition of aluminum, either in the ladle or molds.

(*d*) Spattering the interior sides of the molds in pricking the melts and teeming the ingots to be avoided as much as possible.

(*e*) Time must be allowed for the tops of the ingots to set without spraying with water.

(*f*) The ingots should be stripped as soon as the metal caps over on top, then sent to the scales to be weighed, then sent to the reheating furnaces to be charged promptly, to avoid the cooling of the interior metal and thus check the large shrinkage which occurs in it from unnecessary loss of temperature due to delays. It has been found, in good practice, possible in this way to confine the interior shrinkage to 0.05 to 0.1 of one per cent per cubic foot of the metal of rail ingots. The total shrinkage of an ingot depends upon its volume, chemical composition and loss of temperature at the time it is charged, yet in fair practice it may be confined to such small limits that it is removed in the usual discard of the bloom. Piped rails come from cold ingots or those which have been unduly delayed before charging into the reheating furnace.

(*g*) *Cast Iron Cut Out of the Ingot Stools:* Care to be taken in teeming the ingots to prevent cutting out of the cast iron of the stools or ingot molds by the falling stream of hot metal from the ladle, avoiding a frequent cause of carbon streaks found in the segregated steel of "split heads." The most disturbing factor of the small amount of ordinary segregation in rail steel is the diffused cast iron in some ingots cut out from the stools.

(*h*) Ingots shall be kept in a vertical position on the ingot cars and in the reheating furnaces until their heat is equalized ready to be rolled.

(*i*) Bled ingots shall not be used. ("Bled ingot" — one from the center of which the liquid steel has been permitted to escape.)

(*j*) There shall be sheared from the end of the bloom formed from the top of the ingot sufficient discard to secure sound rails. (All metal from the top of the ingot, whether cut from the bloom or the rail, is the "top discard.")

(*k*) One-hundred-pound (100 lb.) rails not to be rolled from blooms exceeding three (3) thirty-three-foot (33′) lengths in a continuous bar; eighty-pound (80 lb.), or lighter, rails in not over four (4) lengths of thirty-three feet (33′) in a continuous bar, when inserted in the contract.

3rd — **Shrinkage:** The number of passes and speed of train shall be so regulated that, on leaving the rolls on the final pass, the temperature of the rails will not exceed that which requires a shrinkage allowance at the hot saws for a 33-foot rail of 100 pounds section of $6\frac{3}{4}$ inches, and $\frac{1}{16}$ inch less for each five pounds decrease of section. No artificial means of cooling the steel shall be used between the leading and finishing passes, nor after the rails leave the finishing rolls; neither shall rails be held before sawing for the purpose of reducing their temperature.

4th — **Drop and Ductility Tests:** A drop test to be made of a crop from the top bar of the second, the middle and the last full ingot of the melt. The crop 4 to 6 feet long to be stamped with a spacing bar of six one-inch spaces on the base, head or side as desired.

Each butt must show under a single blow of the drop, of 18-foot, for the 80-pound or 90-pound section, and 20-foot for the 100-pound section, at least six per cent elongation for one inch or five per cent each for two consecutive inches before fracture for acceptance of the melt.

The crop or butt is liable to be chilled accidentally in entering the rolls several times, or it may be caused by other delays, and should it break under a single blow without showing the percentage of elongation specified, it shall be considered as indicating deficient ductility or chilled metal, and the results must be rejected.

The Inspecting Engineer representing the Railroad Company must then take a duplicate test from the same ingot at the top end of the "A" or "B" rail, according to the nine or greater percentage of discard, and the results taken in lieu of those from the first crop or test to determine whether or not the piece had the requisite ductility in accordance with the specifications.

The distinction between a chilled test crop and those of inadequate ductility

must be ascertained according to above prescribed tests before rejections are made or rails accepted.

Should any test piece under the first blow of the drop not break, but fail to show the percentage of elongation specified, the test piece shall be subjected in the same position to a second blow and the results so obtained govern in passing the test.

The ductility of at least one specimen of each melt to be exhausted by one or more blows of the drop, and a record made of the respective elongations of each test.

The drop-testing machine shall have a tup of 2000 pounds weight, the striking face of which shall have a radius of not more than five inches (5″), and solid supports, centers three feet (3′) apart, for the test butts. The anvil block shall weigh at least 20,000 pounds and the supports shall be part of or firmly secured to the anvil. The report of drop test shall state the atmospheric temperature at the time the test was made. The testing shall proceed concurrently with the operation of the mill. The temperature of the test butts to be between 40 degrees and 100 degrees Fahr.

5th — Section: The section of rail shall conform to the dimensions furnished by the purchaser as accurately as possible consistent with the paragraph relative to specified weight.

A variation in height of rails of $\frac{1}{32}$ of an inch over or $\frac{1}{64}$ of an inch under, also $\frac{1}{16}$ of an inch in width of flange will be permitted, but no variation will be allowed in dimensions affecting the fit of the splice bars.

6th — Weight: The weight of the rail shall be maintained as nearly as possible, after complying with the preceding paragraph, to that specified in the contract.

A variation of one-half of one per cent, from the calculated weight of section, on the entire order, will be allowed.

Rails will be accepted and paid for according to actual weight.

7th — Length: The standard length of rails shall be thirty-three feet (33′). Ten per cent of the entire order will be accepted in shorter lengths varying as follows: Thirty feet (30′), twenty-eight feet (28′), twenty-six feet (26′) and twenty-four feet (24′). A variation of $\frac{1}{4}$ of an inch from the specified length will be allowed.

Three rails in every 100 tons to be thirty-two feet and six inches (32′ 6″) long, the ends painted red, when inserted in the New York Central Contract.

All other No. 1 rails less than thirty-three feet (33′) long shall be painted green on both ends.

8th — Branding: The name of the maker, the weight of the rail and the month and year of manufacture, together with "O-H," shall be rolled in raised letters on the side of the web, and the number of the melt and letter to designate the position of the rail in the ingot shall be so stamped on each rail as not to be covered by the splice bars.

When the rails are to be rolled with twenty per cent (20%) discard the first rail in the ingot shall commence with the letter "B," the second "C," the third "D" and the fourth "E."

When the "A" rails are to be taken they are to be loaded separately upon cars for shipment and the flanges at the ends painted yellow, when *inserted* in the contract.

9th — Drilling: Circular holes for splice bars shall be drilled in accordance with specifications of purchaser. They shall in every respect accurately conform to drawing and dimensions furnished and shall be free from burrs.

10th — Straightening: Care must be taken in cambering the rails and with the hot-bed work, which must result in the rails being left in such condition that they shall not vary throughout their entire length more than four inches (4″) for the "A. R. A." thick bases and not more than five inches (5″) for the "DUDLEY" section or "A. S. C. E." sections from a straight line *in* any direction when delivered to the cold-straightening presses. Those which vary beyond that amount, or have short kinks, shall be classed as second quality rails and be so marked. Rails while on the "hot-beds" shall be protected from coming in contact with water or snow. The distance between supports of rails in the gagging press shall not be less than forty-two inches (42″); supports to have flat surfaces.

Rails shall be straight in line and surface and smooth on head when finished — final straightening being done while cold. They shall be sawed square at ends, variations to be not more than $\frac{1}{32}$ of an inch, and prior to shipment shall have the burr caused by the saw cutting removed and the ends made clean.

11th — Inspection: The inspector representing the purchaser shall have free entry to the works of the manufacturer at all times while his contract is being executed, and shall have all reasonable facilities afforded him by the manufacturer to satisfy him that the rails are being made in accordance with the terms of the contract. All tests and inspection shall be made at the place of manufacture prior to shipment, and shall be so conducted as not to unnecessarily interfere with the operation of the mill.

The manufacturer shall furnish the inspector with a chemical analysis of

each melt of steel covering the elements specified in the section No. 1 hereof, and also report sulphur and copper.

Analysis shall be made on drillings taken from small test ingots, the drilling being taken at a distance of not less than ¼ of an inch beneath the surface of said test ingots. On request of the inspector the manufacturer shall furnish drillings for check analysis.

12th — **No. 2 Rails**: Rails which by reason of surface imperfections are not classed as No. 1 rails shall be considered No. 2 rails, but No. 2 rails shall not be accepted for shipment which have flaws in the head of more than ¼ of an inch; or in the flange of more than ¼ of an inch in depth; and these shall not, in the judgment of the inspector, be, in any individual rail, so numerous or of such a character as to render it unfit for recognized No. 2 rail uses.

13th — **Designation of No. 2 Rails and Short Lengths of No. 1 Rails**: Both ends of all No. 2 rails shall be painted white.

Both ends of all short lengths No. 1 rails shall be painted green, except the 32-foot and 6-inch rails, which are to be painted red.

(Sgd.) P. H. DUDLEY,
New York Central Lines.

(Specifications of Oct. 1st, 1909.
Revised Jan. 11th, 1911, to conform to Manufacturers' sale per
100 pounds.)

Note 1. "*Process of Manufacture*" (*b*): The elimination of the deoxidation products and impurities from the bath of metal is more important than has yet been appreciated. This prevents minute portions of the deoxidation products from becoming entrained in the setting metal and therefore will avoid their being rolled in the steel, where in the rail head or base they would be subjected to alternate unit fiber strains under moving trains and contribute the needed factor to develop the interior transverse checks recently observed in a few rail heads.

Time is required for the deoxidation products and impurities to rise after the steel is tapped into the ladle.

These heterogeneous portions of the deoxidation products or impurities in the steel, as well as small flaws and interior cavities, are theoretically and practically known to be zones of weakness, and interrupt the normal unit strains and increase them in the surrounding metal, which often result in detailed fractures.

Note 2. "*Process of Manufacture*" (*f*): The percentage of interior shrink-

age per cubic foot of the metal of the ingots there mentioned was reduced the past year by good mill practice and well organized train service. The latter was to transport promptly the ingots after they were teemed and stripped so that they could be charged with the least possible delay into the reheating pits and then as soon as the heat of the metal was properly equalized, they were bloomed, which restricted the reduced cavity to the discard.

Note 1 *and* 2 *added for information.*

P.H.D.

1/3/12

36. British Standard Specifications of Bull Head Railway Rails

(Report No. 9, Revised July, 1909.)

Issued by The Engineering Standards Committee

Supported by: The Institution of Civil Engineers; The Institution of Mechanical Engineers; The Institution of Naval Architects; The Iron and Steel Institute; The Institution of Electrical Engineers. (Reprinted by permission of the Committee).

Chemical Composition.

1. The steel for the Rails shall be of the best quality made by the Bessemer, Siemens-Martin, or other process, as may be approved by the Engineer (or by the Purchaser).

The Rails shall show on analysis that in chemical composition they conform to the following limits:

Carbon	from	0.35 to 0.5	per cent.
Manganese	"	.7 to 1.0	" "
Silicon	not to exceed	0.1	" "
Phosphorus	" "	0.075	" "
Sulphur	" "	0.08	" "

Chemical Analysis.

2. The Manufacturer shall make and furnish to the representative of the Engineer (or of the Purchaser) carbon determinations of each cast.

A complete chemical analysis, representing the average of the other elements contained in the steel, shall be similarly given for each rolling. Such complete analysis shall be made from drillings taken from the rail or tensile test piece or pieces. When the rolling exceeds 200 tons, an additional complete analysis shal be made for each 200 tons or part thereof.

Should the Engineer (or the Purchaser) desire to make independent chemical determinations, the necessary specimens and samples shall be furnished by the Manufacturer. For this purpose not more than two rails in every hundred tons manufactured shall be selected by representative of the Engineer (or of the Purchaser) and drillings taken with a drill of 2 inches diameter from the top of the head of the rail, unless otherwise specified by him, and if, upon being subjected to the specified tests, either fail to comply therewith, then all the Rails in the cast of which the test pieces form a part may be rejected.

The representative of the Engineer (or of the Purchaser) may then take similar samples from a further two rails out of the same 100 tons, and should either fail to comply with the specified analysis the whole 100 tons may be rejected.

In case of difference between the Engineer (or between the Purchaser) and the Manufacturer as to the accuracy of any analysis, either party shall have the right to have samples of the steel analyzed by an independent metallurgist, to be mutually agreed upon. The expenses attendant upon such independent analysis shall be borne by the party adjudged to be in the wrong.

Manufacture.

3. Each Rail shall be made from an ingot not less than 12 inches square at the smaller and 14 inches square at the larger end, and must be cogged down into blooms, and sufficient crop then sheared from each end to ensure soundness.

All straightening shall be done by pressure and not by hammering.

4. A rolling margin of ½ per cent under to ½ per cent above the calculated weight will be permitted, but the calculated weight only will be paid for. **Permissible Variation in Weight.**

5. TABLE OF GENERAL DIMENSIONS AND WEIGHTS OF "B. S." RAILS **General Dimensions of Rails.**

(See Plate XIV)

Number of "B. S." Section and Nominal Weight per Yard in lbs.	Height of Rail.	Width of Head.	Calculated Weight of Rail.
Pounds.	Inches.	Inches.	Pounds per Yard.
60	$4\frac{3}{4}$	$2\frac{5}{16}$	59.79
65	$4\frac{7}{8}$	$2\frac{3}{8}$	64.58
70	5	$2\frac{7}{16}$	70.13
75	$5\frac{1}{8}$	$2\frac{1}{2}$	74.56
80	$5\frac{3}{8}$	$2\frac{9}{16}$	79.49
85	$5\frac{15}{32}$	$2\frac{11}{16}$	84.88
90	$5\frac{35}{64}$	$2\frac{3}{4}$	89.77
95	$5\frac{23}{32}$	$2\frac{3}{4}$	94.59
100	$5\frac{29}{32}$	$2\frac{3}{4}$	99.84

6. Before the general manufacture of the Rails is commenced the Manufacturer shall, if required by the Engineer (or by the Purchaser), supply two sets of templates, internal and external, of approved material, for each "B. S." Section of Rail. **Templates.**

Each template shall be suitably engraved with the Purchaser's name, the number of the "B. S." section (being the nominal weight of the Rail in pounds per lineal yard), the Manufacturers' name and address, and the date of the Contract.

These templates shall be submitted to the Engineer (or to the Purchaser) for his approval, and at the commencement of rolling the Engineer will have a competent person present to approve of the section.

7. Each Section of Rail under this Contract shall be accurately rolled to its respective template. **Rails to Conform to Template.**

8. The whole of the Rails shall be of uniform section throughout, true to templates, perfectly sound and straight, and free from splits, cracks, burrs and defects of every kind. **Rails to be Free from Defects.**

9. A quantity of short lengths will be taken in such lengths and quantities as may be ordered by the Engineer (or by the Purchaser), provided that these short lengths are cut down from longer lengths found to be defective at the ends only, and that the total quantity taken does not exceed 7½ per cent of the contract. **Length of Rails for Straight Line.**

N. B. — The Committee recommend the adoption of the following, as the normal lengths of Rails, viz.: — 30 feet, 36 feet, 45 feet, or 60 feet.

10. The Rails shall be the specified length at the temperature of 60° Fahr. No Rail will be accepted which is more than three-sixteenths of an inch ($\frac{3}{16}$ inch) above or below the length specified, whether for curved or straight line. **Permissible Variation in Length.**

11. When required by the Engineer (or by the Purchaser) rails are to be supplied from 1 to 6 inches shorter or longer than the normal specified lengths, and these special lengths are to have about one foot at each end painted with such colors as may be ordered. **Rails of Special Length for Matching in Curved Line.**

12. Rails shall be supplied for switches and crossings when so ordered, and such Rails shall be of the required lengths and shall be cut from sound long Rails. **Rails for Switches and Crossings.**

13. The Brand shall be rolled on the web of each Rail to show that the Rail is of British Standard Section and made under the conditions of this Specification; the number of the "B. S." Section (being the nominal weight of the Rail in pounds per yard), the process by which the Rails have been manufactured, the Manufacturer's name, initials, or other recognized mark, and the month and year of manufacture shall be rolled, in letters three-quarters of an inch (¾ inch) in size, on one **Branding.**

side of the web of each Rail, e.g., B.S. 95, B.A.*.......4.04; and the number of the cast or blow from which it has been rolled shall be stamped on the end of each Rail in half-inch (½ inch block figures.

Impact Test.

14. From each cast one rail shall be selected by the representative of the Engineer (or of the Purchaser). From this a piece 5 feet long shall be cut which shall be placed in a horizontal position with the bullhead uppermost upon two iron or steel supports resting on a solid foundation and placed so that their centers are 3 feet 6 inches apart, the upper surfaces of the supports being curved to a radius of 3 inches. The test shall comprise two blows delivered midway between the bearings from a falling iron weight of 2240 pounds, the striking face of which shall be rounded to a radius of not more than 5 inches. The heights of the drop for the various sections of Rails shall be as tabulated below. The blows must be sustained without fracture, and the Rail must show a deflection between the limits given below.

FALLING WEIGHT TEST

Number of "B. S." Section and Nominal Weight of Rails per Yard in lbs.	Drop.	First Blow Deflection.		Drop.	Second Blow Deflection.	
		From.	To.		From.	To.
Pounds.	Feet.	Inches.		Feet.	Inches.	
60	5	1	$1\frac{5}{16}$	10	3	$3\frac{3}{4}$
65	5	1	$1\frac{1}{4}$	12	3	$3\frac{3}{4}$
70	6	1	$1\frac{5}{16}$	12	3	$3\frac{3}{4}$
75	6	1	$1\frac{5}{16}$	12	3	$3\frac{3}{4}$
80	6	$\frac{7}{8}$	$1\frac{3}{16}$	15	3	4
85	6	$\frac{7}{8}$	$1\frac{3}{16}$	15	3	4
90	7	$\frac{7}{8}$	$1\frac{1}{4}$	20	3	$4\frac{1}{4}$
95	7	$\frac{7}{8}$	$1\frac{3}{16}$	20	3	$4\frac{1}{4}$
100	7	$\frac{7}{8}$	$1\frac{3}{16}$	20	3	$4\frac{1}{4}$

Should the length cut from the selected Rail fail to comply with the test specified for its weight, two other Rails from the same cast will be selected and similar lengths cut and tested, and the acceptance or rejection of the cast will be decided by the result of the three tests, so that if two of the Rails selected fail to comply with the test, the entire cast will be rejected.

Tensile Test.

15. From each 100 tons of Rails the Manufacturer shall (if required by the representative of the Engineer or of the Purchaser) cut a test piece from any Rail selected as a sample Rail; such test piece to be stamped to correspond with the sample Rail. It shall then be placed in a testing machine of approved pattern, and shall have an ultimate tensile strength equivalent to not less than 40 tons per square inch, nor more than 48 tons per square inch, with an elongation of not less than 15 per cent upon the Standard Test Pieces *C* or *D* (see Fig. 341). Should the test piece fail to fulfil these conditions, the representative of the Engineer (or of the Purchaser) may require the Manufacturer to test two other Rails from the same cast in the same manner, and the acceptance or rejection of the cast shall be decided by the results of the three tests so that if two of the three Rails selected fail to comply with the test the entire cast will be rejected.

The representative of the Engineer (or of the Purchaser) may then take similar test pieces from a further two rails out of the same 100 tons, and should either fail to comply with the test the whole 100 tons may be rejected.

Should the Engineer (or the Purchaser) desire to have independent tests made, the Manufacturer shall provide the necessary test pieces, viz., two for every 200 tons, properly shaped and prepared as described in Fig. 341.

* The following abbreviations are recommended:

S.A. Siemens-Martin Acid.	B.A. Bessemer Acid.
S.B. Siemens-Martin Basic.	B.B. Bessemer Basic.

16. The holes for fishbolts must be drilled through the web from the solid at each end of the Rails, of the sizes and in the position shown in the British Standard specification for Fish plates for Bull Head Rails (Report No. 47) or on a drawing to be supplied by the Engineer (or the Purchaser). These holes must be clean and square with the web, without burrs on either side, and will be checked with the gauges to be furnished to the Manufacturer by the Engineer (or by the Purchaser). Should any of the holes vary from the correct size or position more than one thirty-second of an inch ($\frac{1}{32}$ inch) the Rails in question will be liable to rejection. **Holes in Rails.**

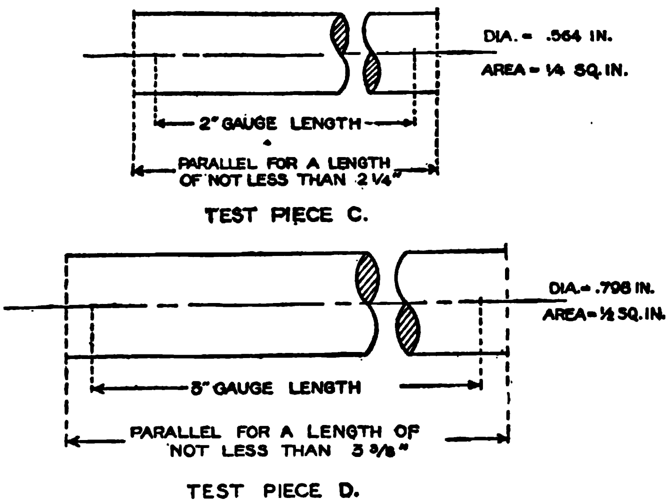


Fig. 341. — Test Pieces *C* and *D*, British Standard Specifications of Rails.

The gauge length and the parallel portion are to be as shown, the form of the ends to be as required in order to suit the various methods employed for gripping the test piece.

17. The Manufacturer shall give to the Engineer (or to the Purchaser), or his representative, at least seven clear days' previous notice, in writing, before the rolling of the first lot of Rails, and at least three clear days' previous notice, in writing, before the rolling of any subsequent lot of Rails, is commenced, in order that arrangements may be made for the presence of the representative of the Engineer (or of the Purchaser) at the rolling. **Notice of Rolling to be Given.**

18. The Engineer (or the Purchaser) or his representative shall have access to the works of the Manufacturer at all reasonable times. He shall be at liberty to examine the Rails during any stage of their manufacture, and to reject any material or finished Rail which does not conform to the terms of this specification. **Inspection and Testing.**

Before the Rails are put before the representative of the Engineer (or of the Purchaser) for inspection the Manufacturer shall have them examined, and all Rail which he admits to be defective are to be sorted out and placed in a separate stack; the representative of the Engineer (or of the Purchaser) being empowered to refuse to inspect any lot of Rails not put in uniform lengths and sorted.

19. The Manufacturer shall supply the material required for testing free of charge and shall, at his own cost, furnish and prepare the necessary test pieces, and supply labor and appliances for such testing as may be carried out at his premises in accordance with this specification. Failing facilities at his own works for making the prescribed tests the Manufacturer shall bear the cost of carrying out the tests elsewhere.

20. All Rails accepted by the representative of the Engineer (or of the Purchaser) shall be stamped in his presence. **Marking of Accepted Rails.**

37. British Standard Specifications of Flat Bottom Railway Rails

(Report No. 11, Revised July, 1909)

Issued by The Engineering Standards Committee

Supported by: The Institution of Civil Engineers; The Institution of Mechanical Engineers; The Institution of Naval Architects; The Iron and Steel Institute; The Institution of Electrical Engineers. (Reprinted by permission of the Committee.)

Chemical Composition.

1. The steel for the Rails shall be of the best quality made by the Bessemer, Siemens-Martin, or other process, as may be approved by the Engineer (or by the Purchaser).

The Rails shall show on analysis that in chemical composition they conform to the following limits:

Carbon	from	0.35 to 0.50 per cent.
Manganese	"	0.70 to 1.00 " "
Silicon	not to exceed	0.10 " "
Phosphorus	" " "	0.07 " "
Sulphur	" " "	0.07 " "

Chemical Analysis.

2. The Manufacturer shall make and furnish to the representative of the Engineer (or of the Purchaser) carbon and phosphorus determinations of each cast.

A complete chemical analysis, representing the average of the other elements contained in the steel, shall be similarly given for each rolling. Such complete analysis shall be made from drillings taken from the Rail or from the tensile test piece or pieces. When the rolling exceeds 200 tons, an additional complete analysis shall be made for each 200 tons or part thereof.

Should the Engineer (or the Purchaser) desire to make independent chemical determinations, the necessary specimens and samples shall be furnished by the Manufacturer. For this purpose not more than two Rails in every 100 tons manufactured shall be selected by the representative of the Engineer (or of the Purchaser) and drillings taken with a drill of 2 inches diameter from the top of the head of the Rail unless otherwise specified by him, and if, upon being subjected to the specified tests, either fail to comply therewith, then all the Rails in the cast of which the test pieces form a part may be rejected.

The representative of the Engineer (or of the Purchaser) may then take similar samples from a further two rails out of the same 100 tons, and should either fail to comply with the specified analysis the whole 100 tons may be rejected.

In case of difference between the Engineer (or between the Purchaser) and the Manufacturer, as to the accuracy of an analysis, either party shall have the right to have samples of the steel analyzed by an independent metallurgist, to be mutually agreed upon The expenses attendant upon such independent analysis shall be borne by the party adjudged to be in the wrong.

Manufacture.

3. Each Rail shall be made from an ingot not less than 12 inches square at the smaller end and 14 inches square at the larger end, which must be cogged down into blooms, and have sufficient crop then sheared from each end to ensure soundness.

All straightening shall be done by pressure and not by hammering.

Permissible Variation in Weight.

4. A rolling margin of ½ per cent under to ½ per cent above the calculated weight will be permitted, but the calculated weight only will be paid for.

Templates.

6. Before the general manufacture of the Rails is commenced the Manufacturer shall, if required by the Engineer (or by the Purchaser), supply two sets of templates, internal and external, of approved material, for each " B. S." Section of Rail.

Each template shall be suitably engraved with the Purchaser's name, the number of the " B. S." section (being the nominal weight of the Rail in pounds per yard), the Manufacturer's name and address, and the date of the Contract.

These templates shall be submitted to the Engineer (or to the Purchaser) for his approval, and at the commencement of rolling the Engineer will have a competent person present to approve of the section.

General Dimensions and Weights of Rails.

6. TABLE OF GENERAL DIMENSIONS AND WEIGHTS OF "B. S." RAILS

(See Plate XV)

Number of "B. S." Section and Nominal Weight per Yard in Pounds.	Height of Rail.	Width of Head.	Calculated Weight of Rail.
	Inches.	Inches.	Pounds per Yard.
20	$2\frac{1}{2}$	$1\frac{3}{8}$	19.96
25	$2\frac{3}{4}$	$1\frac{1}{2}$	24.95
30	3	$1\frac{5}{8}$	29.98
35	$3\frac{1}{4}$	$1\frac{3}{4}$	35.03
40	$3\frac{1}{2}$	$1\frac{7}{8}$	39.98
45	$3\frac{3}{4}$	$1\frac{31}{32}$	45.10
50	$3\frac{15}{16}$	$2\frac{1}{16}$	49.94
55	$4\frac{1}{8}$	$2\frac{5}{32}$	54.78
60	$4\frac{5}{16}$	$2\frac{1}{4}$	60.11
65	$4\frac{7}{16}$	$2\frac{5}{16}$	64.86
70	$4\frac{5}{8}$	$2\frac{3}{8}$	69.77
75	$4\frac{13}{16}$	$2\frac{7}{16}$	74.79
80	5	$2\frac{1}{2}$	79.94
85	$5\frac{3}{16}$	$2\frac{9}{16}$	84.87
90	$5\frac{3}{8}$	$2\frac{5}{8}$	89.92
95	$5\frac{9}{16}$	$2\frac{11}{16}$	94.76
100	$5\frac{3}{4}$	$2\frac{3}{4}$	99.95

Rails to Conform to Templates.

7. Each Section of Rail shall be accurately rolled to its respective template.

Rails to be Free from Defects.

8. The whole of the Rails shall be of uniform section throughout, true to templates, perfectly sound and straight, and free from splits, cracks, burrs, and defects of every kind.

Length of Rails for Straight Line.

9. A quantity of short lengths will be taken in such lengths and quantities as may be ordered by the Engineer (or by the Purchaser), provided that these short lengths are cut down from longer lengths found to be defective at the ends only, and that the total quantity taken does not exceed $7\frac{1}{2}$ per cent of the Contract.

Permissible Variation in Length.

10. The Rails shall be the specified length at a temperature of 60° Fahr. No Rail will be accepted which is more than three-sixteenths of an inch ($\frac{3}{16}$ inch) above or below the length specified, whether for straight or curved lines.

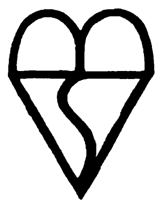
Rails of Special Length for Matching in Curved Line.

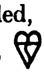
11. When required by the Engineer (or by the Purchaser) Rails are to be supplied from 1 to 6 inches shorter or longer than the normal specified lengths, and these special lengths are to have about one foot at each end painted with such colors as may be ordered.

Rails for Switches and Crossings.

12. Rails shall be supplied for switches and crossings when so ordered, and such Rails shall be of the required lengths and shall be cut from sound Rails.

Branding.



13. The Brand (see sketch) shall be rolled on the web of each Rail to show that the Rail is of British Standard Section and made under the conditions of this Specification; the number of the " B. S." Section (being the nominal weight of the Rail in pounds per yard), the process* by which the Rails have been manufactured, the Manufacturer's name, initials, or other recognized mark, and the month and year of manufacture shall also be rolled, in letters three-quarters of an inch ($\frac{3}{4}$ inch) in size, on one side of the web of each Rail, e.g.,  B.S. 95–B.A.*.......4.04; and the number of the cast from which it has been rolled shall be stamped on the end of each Rail in half-inch ($\frac{1}{2}$ inch) block figures.

Impact Test.

14. From each cast a piece of Rail (which may be a crop end) shall be selected by the representative of the Engineer (or of the Purchaser) and stamped with his mark and the number of the cast. From this a piece 5 feet long shall be cut which shall be placed in a horizontal position, with the head uppermost, upon two iron or steel supports resting on a solid foundation, the upper

* The following abbreviations are recommended:—

S.A.	Siemens-Martin Acid.	B.A.	Bessemer Acid.
S.B.	Siemens-Martin Basic.	B.B.	Bessemer Basic.

surfaces of the supports being curved to a radius of 3 inches. The test shall comprise one blow, delivered midway between the bearings, from a falling iron weight or tup, the striking face of which shall be rounded to a radius of not more than 5 inches. The weight of the tup, the span of the test piece between the centers of the bearings, and the height of the drop for the various sections of Rails shall be as tabulated below. The blow must be sustained without fracture. In addition to the above test the representative of the Engineer (or of the Purchaser) shall select one finished Rail from every 200 offered, and a piece 5 feet in length cut from this Rail shall be similarly tested as specified above.

Number of "B. S." Section and Nominal Weight of Rails per Yard in Pounds.	Falling Weight Test.		
	Weight of Tup.	Centers of Bearings.	Drop.
	Cwts.	Feet.	Feet.
20	5	3	8
25	5	3	9
30	10	3	10
35	10	3	12½
40	10	3	15
45	15	3	15
50	15	3	15
55	15	3	17½
60	20	3	20
65	20	3	20
70	20	3½	20
75	20	3½	20
80	20	3½	22
85	20	3½	24
90	20	3½	26
95	20	3½	28
100	20	3½	30

Should the length cut from the selected Rail fail to comply with the test specified for its weight, two other Rails from the same cast will be selected and similar lengths cut and tested, and the acceptance or rejection of the cast will be decided by the result of the three tests, so that if two of the Rails selected fail to comply with the test the entire cast will be rejected.

Tensile Test. 15. From each 100 tons of Rails the Manufacturer shall (if required by the representative of the Engineer or of the Purchaser) cut a test piece from any Rail selected as a sample Rail; such test piece to be stamped to correspond with the sample Rail. It shall then be placed in a testing machine of approved pattern, and shall have an ultimate tensile strength of not less than 40 tons per square inch, nor more than 48 tons per square inch, with an elongation of not less than 15 per cent upon the Standard Test Pieces C or D (see Fig. 341). Should the test piece fail to fulfil these conditions, the representative of the Engineer (or of the Purchaser) may require the Manufacturer to test two other Rails from the same cast in the same manner, and the acceptance or rejection of the cast shall be decided by the result of the three tests, so that if two of the three Rails selected fail to comply with the test the entire cast will be rejected.

The representative of the Engineer (or of the Purchaser) may then take similar test pieces from a further two Rails out of the same 100 tons, and should either fail to comply with the test the whole 100 tons may be rejected.

Should the Engineer (or the Purchaser) desire to have independent tests made, the Manufacturer shall provide the necessary test pieces, viz., two for every 200 tons, properly shaped and prepared as described in Fig. 341.

Holes in Rails. 16. The holes for fishbolts shall be drilled through the web from the solid at each end of the Rails, of the sizes and in the position shown in the British Standard Specification for Fish Plates for Flat Bottom Rails (Report No. 47), or on a drawirg to be supplied by the Engineer (or by the Purchaser). These holes must be clean and square with the web, without burrs on

either side, and will be checked with the gauges to be furnished to the Manufacturer by the Engineer (or by the Purchaser). Should any of the holes vary from the correct size or position more than one thirty-second of an inch ($\frac{1}{32}$ inch) the Rails in question will be liable to rejection.

17. The Manufacturer shall give to the Engineer (or to the Purchaser), or his representative, at least seven clear days' previous notice, in writing, before the rolling of the first lot of Rails, and at least three clear days' previous notice, in writing, before the rolling of any subsequent lot of Rails, is commenced, in order that arrangements may be made for the presence of the representative of the Engineer (or of the Purchaser) at the rolling. **Notice of Rolling to Be Given.**

18. The Engineer (or the Purchaser), or his representative, shall have free access to the works of the Manufacturer at all reasonable times: he shall be at liberty to examine the Rails during any stage of their manufacture, and to reject any material or finished Rail which does not conform to the terms of this Specification. **Inspection and Testing.**

Before the Rails are put before the representative of the Engineer (or of the Purchaser) for inspection, the Manufacturer shall have them examined, and all Rails which he admits to be defective shall be sorted out and placed in a separate stack; the representative of the Engineer (or of the Purchaser) being empowered to refuse to inspect any lot of Rails not put in uniform lengths and sorted.

19. The Manufacturer shall supply the material required for testing free of charge and shall, at his own cost, furnish and prepare the necessary test pieces, and supply labor and appliances for such testing as may be carried out on his premises in accordance with this Specification. Failing facilities at his own works for making the prescribed tests, the Manufacturer shall bear the cost of carrying out the tests elsewhere. **Testing Facilities.**

20. All Rails accepted by the representative of the Engineer (or of the Purchaser) shall be stamped in his presence. **Marking of Accepted Rails**

38. Specifications for Street Railway Rails

American Society for Testing Materials, Affiliated with the International Association for Testing Materials.— Standard Specifications for Open-hearth Steel Girder and High Tee Rails. Adopted June 1, 1912.

I. Manufacture

1. The steel shall be made by the open-hearth process. The entire process of manufacture and testing shall accord with the best current practice. **Process.**

2. Bled ingots, and ingots or blooms which show the effects of injurious treatment, shall not be used. **Bled Ingots.**

3. A sufficient discard from the top of each ingot shall be made at any stage of the manufacture to obtain sound rails. When finished rails show piping, they may be cut to shorter lengths until all evidence of this is removed. **Discard.**

II. Chemical Properties and Tests

4. The steel shall conform to either of the following requirements as to chemical composition, as specified in the order: **Chemical Composition.**

	Class A.	Class B.
Carbon, per cent	0.60–0.75	0.70–0.85
Manganese, per cent	0.60–0.90	0.60–0.90
Silicon, per cent	not over 0.20	not over 0.20
Phosphorus, per cent	not over 0.04	not over 0.04

5. To determine whether the material conforms to the requirements specified in Section 4, an analysis shall be made by the manufacturer from a test ingot taken during the pouring of each melt. Drillings for analysis shall be taken not less than $\frac{1}{8}$ inch beneath the surface of the test ingot. A copy of this analysis shall be given to the purchaser or his representative. **Ladle Analyses.**

6. A Check analysis may be made from time to time by the purchaser from a test ingot or drillings therefrom furnished by the manufacturer. **Check Analyses.**

III. Physical Properties and Tests

Drop Tests.

7. (*a*) The test specimen shall be tested on a drop-test machine of the type recommended by the American Railway Engineering Association. The specimen shall be placed head upward on the supports of the machine, and shall not break when tested with one blow in accordance with the following conditions:

Weight and Height of Rail.	Temperature of Specimens, deg. Fahr.	Distance between Supports, ft.	Weight of Tup, lb.	Height of Drop.	
				Class A.	Class B.
Rails weighing over 100 lb. per yd. and over 7 in. in depth.........	60–120	3	2000	15	12
Rails weighing 100 lb. or less per yd., or 7 in. or less in depth....	60–120	3	2000	13	10

(*b*) The atmospheric temperature at the time of testing shall be recorded in the test report.

(*c*) The testing shall proceed concurrently with the operation of the works.

Test Specimens.

8. (*a*) Three rails, each from the top of one of three ingots from each melt, shall be selected by the inspector, and a test specimen shall be taken from each of two of these.

(*b*) Drop test specimens shall not be less than 4, nor more than 6 feet in length.

Number of Tests.

9. Two drop tests shall be made from each melt.

Retests.

10. If the result of the drop test on only one of the two specimens representing the rails in a melt does not conform to the requirements specified in Section 7, a retest on a specimen from the third rail selected shall be made and this shall govern the acceptance or rejection of the rails from that melt.

IV. Standard Sections, Lengths, and Weights

Section.

11. (*a*) The cold templet of the manufacturer shall conform to the specified section as shown in detail on the drawing of the purchaser, and shall at all times be maintained perfect.

(*b*) The section of the rail shall conform as accurately as possible to the templet, and within the following tolerances:

(1) The height shall not vary more than $\frac{1}{64}$ inch under nor more than $\frac{1}{32}$ inch over that specified.

(2) The over-all width of head and tram shall not vary more than $\frac{1}{8}$ inch from that specified. Any variation which would affect the gage line more than $\frac{1}{32}$ inch will not be allowed.

(3) The width of base shall not vary more than $\frac{1}{8}$ inch under that specified for widths less than $6\frac{1}{2}$ inches; $\frac{3}{16}$ inch under for a width of $6\frac{1}{2}$ inches; and $\frac{1}{4}$ inch under for a width of 7 inches.

(4) Any variation which would affect the fit of the splice bars will not be allowed.

(5) The base of the rail shall be at right angles to the web; and the convexity shall not exceed $\frac{1}{32}$ inch.

(*c*) When necessary on account of the type of track construction, and notice to that effect has been given to the manufacturer, special care shall be taken to maintain the proper position of the gage line with respect to the outer edge of the base.

Length.

12. (*a*) Unless otherwise specified, the lengths of rails at a temperature of 60° F. shall be 60 and 62 feet for those sections in which the weight per yard will permit.

(*b*) The lengths shall not vary more than $\frac{1}{4}$ inch from those specified.

(*c*) Shorter lengths, varying by even feet down to 40 feet, will be accepted to the extent of 10 per cent by weight of the entire order.

13. (*a*) The weight of the rails per yard as specified in the order shall be maintained as nearly as possible after conforming to the requirements specified in Section 11. **Weight.**

(*b*) The total weight of an order shall not vary more than 0.5 per cent from that specified.

(*c*) Payments shall be based on actual weights.

V. Workmanship and Finish

14. (*a*) Rails on the hot beds shall be protected from water or snow, and shall be carefully manipulated to minimize cold straightening. **Straightening.**

(*b*) The distance between the rail supports in the cold-straightening presses shall not be less than 42 inches, except as may be necessary near the ends of the rails. The gag shall have rounded corners to avoid injury to the rails.

15. (*a*) Circular holes for joint bolts, bonds, and tie rods shall be drilled to conform to the drawings and dimensions furnished by the purchaser. **Drilling and Punching.**

(*b*) In Class A rails the tie-rod holes may be punched.

16. The ends shall be milled square laterally and vertically, but the base may be undercut $\frac{1}{32}$ inch. **Milling.**

17. (*a*) Rails shall be smooth on the head, straight in line and surface without any twists, waves, or kinks, particular attention being given to having the ends without kinks or drop. **Finish.**

(*b*) All burrs or flow caused by drilling or sawing shall be carefully removed.

(*c*) Rails shall be free from gag marks and other injurious defects of cold-straightening.

VI. Classification of Rails

18. Rails which are free from injurious defects and flaws of all kinds shall be classed as No. 1 Rails. **No. 1 Rails.**

19. (*a*) Rails which are rough on the head or which by reason of surface or other imperfections are not classed as No. 1 rails, shall be classed as No. 2 rails; providing they do not, in the judgment of the inspector, contain imperfections in such number and of such character as to render them unfit for No. 2 rail uses, and providing they conform to the requirements specified in Section 11. **No. 2 Rails.**

(*b*) Rails which have flaws in the head exceeding $\frac{1}{4}$ inch in depth, or in the base exceeding $\frac{1}{8}$ inch in depth, shall not be classed as No. 2 rails.

(*c*) No. 2 rails will be accepted to the extent of 10 per cent by weight of the entire order.

VII. Marking and Loading

20. (*a*) The name or brand of the manufacturer, the year and month of manufacture, the letters "O. H.," the weight of the rail, and the section number shall be legibly rolled in raised letters and figures on the web. The melt number shall be legibly stamped on each rail where it will not be covered subsequently by the joint plates. **Marking.**

(*b*) Both ends of all short-length No. 1 rails shall be painted green.

Both ends of all No. 2 rails shall be painted white and shall have two heavy center-punch marks on the web at each end at such a distance from the end that they will not be covered subsequently by the joint plates.

21. (*a*) Rails shall be loaded in the presence of the inspector, and shall be handled in such a manner as not to bruise the flanges or cause other injuries. **Loading.**

(*b*) Rails of each class shall be placed together in loading.

(*c*) Rails shall be paired as to length before shipment.

VIII. Inspection

22. The inspector representing the purchaser shall have free entry, at all times while work on the contract of the purchaser is being performed, to all parts of the manufacturer's works **Inspection.**

which concern the manufacture of the material ordered. The manufacturer shall afford the inspector, free of cost, all reasonable facilities to satisfy him that the material is being furnished in accordance with these specifications. All tests and inspection shall be made at the place of manufacture prior to shipment, and shall be so conducted as not to interfere unnecessarily with the operation of the works.

39. Bibliography of Rail Specifications

Search furnished by the Secretary of the American Society of Civil Engineers, and made in its Library, January 24, 1910, and January 19, 1912, supplemented by the Technology department of the Carnegie Library of Pittsburgh.

1877

" Permanent-way Rolling Stock and Technical Working of Railways," Vol. 1, p. 512, by Ch. Couche, tr. by James N. Shoolbred. Paris, 1877. Dunod, 49 Quai des Augustins. (Contains specifications for chemical composition of steel rails.)

1879

" The Chemical Composition and Physical Properties of Steel Rails," by C. B. Dudley. Trans. Am. Inst. Min. Engrs., Vol. 7, p. 172 (1879). (Recommends a formula for the chemical composition of rails for the use of the Pennsylvania Railroad.)

" Does the Wearing Power of Steel Rails Increase with the Hardness of Steel? " by Charles B. Dudley. Trans. Am. Inst. Min. Engrs , Vol. 7, p. 202 (1879) (four pages).

" Discussion of Dr. Charles B. Dudley's Papers on Steel Rails." Trans. Am. Inst. Min. Engrs., Vol. 7, p. 357 (1879)

1880

" The Wearing Capacity of Steel Rails in Relation to their Chemical Composition and Physical Properties," by Charles B. Dudley. Trans. Am. Inst. Min. Engrs., Vol. 8, p. 321 (1880). (Contains references to specifications for chemical composition.)

1888

" Specifications for Steel Rails and Track Fastenings." Eng. News, Vol. 20, p. 172 (Sept. 1, 1888). (Specifications drawn up and used by Frank Ward & Bro., of Pittsburg, Pa.)

Same. R. R. Gaz., Vol. 20, p. 587 (Sept. 7, 1888).

" Steel Rails and Specifications for their Manufacture," by Robert W. Hunt. Trans. Am. Inst. Min. Engrs., Vol. 17, p. 226 (1888). (Contains specifications for Bessemer steel rails.)

Abstracts of same. R. R. Gaz., Vol. 20, p. 697 (Oct. 26, 1888); Eng. and Min. Jour., Vol. 46, p. 370 (Nov. 3, 1888).

1893

" Steel Rails: their Manufacture and Service." Eng. News, Vol. 30, p. 172 (Aug. 31, 1893). (Proposed specifications for steel rails.)

1895

" Specifications for Steel Rails of Heavy Sections Manufactured West of the Alleghenies," by Robert W. Hunt. Trans. Am. Inst. Min. Engrs., Vol. 25, p. 653 (1895). (The author states that " the only important features in which the present specifications differ from those of 1888 is in providing for a chemical composition and for drop tests.")

1897

" Brief Note on Rail Specifications," by Robert W. Hunt. Trans. Am. Inst. Min. Engrs., Vol. 27, p. 139 (1897). (One page; report of progress.)

1899

"Specifications on Structural Steel and Rails," by W. R. Webster. Journal of the Franklin Institute, Vol. 147, p. 1 (Jan., 1899). (General discussion of the subject.)

1900

Proceedings American Railway Engineering and Maintenance of Way Association, Vol. 1, p. 116 (1900). (Refers to specifications for steel rails.)

"Recent Practice in Rails: an Informal Discussion." Trans. Am. Socy. of Civ. Engrs., Vol. 44, p. 489 (Paper 887, Dec., 1900). (Gives the standard rail specifications of the Louisville & Nashville R. R. Co., Robert W. Hunt's specifications, and specifications of the Western rail mills, and a review of foreign rail specifications.)

"American Standard Specifications and Methods of Testing Iron and Steel," by Albert Ladd Colby. Journal of the Iron and Steel Institute, Vol. 158, p. 215 (1900). (Gives specifications for steel rails.)

1901

"Proposed Standard Specifications for Steel Rails." In Proc. Am. Ry. Eng. and M. of W. Assn., Vol. 2, p. 192 (1901). (Specifications recommended by Committee No. 1 of the American Section of the International Association for Testing Materials.)

"Nature of Metal for Rails, Report (United States)," by P. H. Dudley. International Railway Congress. Proceedings, Sixth Session, 1900, Vol. 1, Question 1, pp. 205, 248. Brussels, 1901. P. Weissenbruch, 49 Rue du Poinçon. (Gives specifications for steel rails.)

"Examen des Specifications Normales Americaines Proposées Éprouvettes et Méthodes d'Essai du Fer et de l'Acier," by Albert Ladd Colby. In "Communications Présentées devant le Congrès International des Méthodes d'Essai des Matériaux de Construction tenu à Paris du 9 au 16 Juillet, 1900," Vol. 2, Pt. 1, pp. 147, 162. Paris, 1901. Vve. Ch. Dunod, 49 Quai des Grands-Augustins. (Contains a review of foreign specifications for steel rails and proposed American standard specifications.)

"Specifications for Steel Rails," by P. H. Dudley. R. R. Gaz., Vol. 33, p. 158 (March 8, 1901) (one page).

"Some Suggestions as to Specifications for Steel Rails," by E. F. Kenney. Eng. News, Vol. 46, p. 226 (Oct. 3, 1901).

1902

American Society for Testing Materials, Proceedings, Vol. 1, pp. 101, 264 (1899–1902). (Proposed standard specifications for steel rails recommended by American Branch of Committee No. 1, American Section of the International Association for Testing Materials.

"Review and Text of the American Standard Specifications for Steel, adopted in August, 1901," p. 41, by Albert Ladd Colby. Ed. 2. Easton, Pa., 1902. The Chemical Publishing Co. (Contains specifications for steel rails.)

"Proposed Modifications of the Standard Specifications for Steel Rails, Topical Discussion." Proc. Am. Socy. for Testing Materials, Vol. 2, p. 9, 23 (1902).

Proceedings of the Am. Ry. Eng. and M. of W. Assn., Vol. 3, p. 201 (1902). (Specifications recommended in 1901 with some amendments.)

"Specifications for Steel Rails," by W. R. Webster, Trans. Am. Inst. Min. Engrs., Vol. 31, pp. 449, 967 (1902). (Contains proposed standard specifications recommended May, 1900, by the American Branch of Committee No. 1 of the International Association for Testing Materials.)

"Steel Rails: Specifications," by Robert Job. Am. Eng. and R. R. Jour., Vol. 76, p. 310 (Oct., 1902). (Gives specifications of the Philadelphia & Reading Railway Company for steel rails.)

1903

"The Present Situation as to Specifications for Steel Rails," by William R. Webster. Trans. Am. Inst. Min. Engrs., Vol. 33, p. 164 (1903) (five pages).

"Proposed Modifications in the Specifications for Steel Rails adopted by the American Railway Engineering and Maintenance of Way Association in March, 1903." Proc. Am. Socy. for Testing Materials, Vol. 3, p. 74 (1903).

1904

" British Standard Specification and Sections of Bullheaded Railway Rails." Engineering Standards Committee. Report No. 9. Lond., 1904. (10*s*. 6*d*. net.)

" Specifications for Steel Rails of the American Railway Engineering and Maintenance of Way Association, as Amended and Adopted in March, 1904," with Introduction by William R. Webster. Proc. Am. Socy. for Testing Materials, Vol. 4, p. 195 (1904). (Showing main difference in specifications adopted by the two societies.)

" Standard Specifications for Bessemer Steel Rails." In Proc. Am. Ry. Eng. and M. of W. Assn., Vol. 5, p. 465 (1904).

" Specifications for Bessemer Steel Rails." Eng. News, Vol. 50, p. 275 (March 24, 1904). (Gives specifications adopted by the American Railway Engineering and Maintenance of Way Association.)

1905

" Railroad Construction," p. 243; by Walter Loring Webb, M. Am. Socy. C. E. Ed. 3. N. Y., 1905, John Wiley & Sons, 43 E. 19th St. (Contains proposed standard specifications for steel rails of the American Railway Engineering and Maintenance of Way Association, March, 1902.)

British Standard Specification and Sections of Flat-bottomed Railway Rails. Engineering Standards Committee. Report No. 11. Lond., 1905. Leslie S. Robertson, Secy., 28 Victoria Street, Westminster, S. W. (10*s*. 6*d*. net.)

" Steel Rails," by William R. Webster. R. R. Gaz., Vol. 38, p. 440 (May 5, 1905). (Gives specifications of the American Railway Engineering and Maintenance of Way Association.)

1906

" On Specifications for Steel Rails." Proc. Am. Socy. for Testing Materials, Vol. 6, p. 35 (1906). (Gives proposed standard specifications for steel rails.)

Proc. Am. Ry. Eng. and M. of W. Assn. Vol. 7, p. 553 (1906). (Gives comparison of specifications of American Railway Engineering and Maintenance of Way Association and the American Society of Civil Engineers.)

" Rails for Lines with Fast Trains." Reports; by P. H. Dudley and Van Bogaert. International Railway Congress, Seventh Session, 1905, Vol. 1, Question 2, pp. 141, 194. Brussels, 1906. P. Weissenbruch. (Contains very brief data on rails specifications.)

" Specifications for Steel Rails." R. R. Gaz., Vol. 40, p. 280 (March 16, 1906). (Specifications recommended by the American Railway Engineering and Maintenance of Way Association, American Society for Testing Materials, and American Society of Civil Engineers.)

1907

" Report of the Special Committee on Rail Sections to the American Society of Civil Engineers." Proc. Am. Socy. of Civ. Engrs., Vol. 32, p. 52; Vol. 33, p. 290 (1906, 1907). (Contains recommended specifications for Bessemer steel rails.)

" Manual of Recommended Practice for Railway Engineering and Maintenance of Way," p. 55. Am. Ry. Eng. and M. of W. Assn. Edition of 1907. (Contains specifications for rails.)

" Proposed Standard Specifications for Steel Rails." Proc. Am. Socy. for Testing Materials, Vol. 7, p. 40 (1907). (Specifications adopted Sept. 1, 1907.)

" The Steel-rail Discussion, American Society for Testing Materials." Ry. and Eng. Review, Vol. 47, p. 570 (June 29, 1907).

" Proceedings of the Session of the American Railway Association, October 30, 1907," p. 175, N. Y., 1907. (Report of the Committee on Rail Sections giving specifications for Bessemer steel rails with explanatory notes.)

"Standard Specifications for Steel Rails." Proc. Am. Soc. for Testing Materials, Vol. 7, p. 44 (1907).

Same. Eng. Record, Vol. 55, p. 774 (June 29, 1907).

Comparison of American and Foreign Rail Specifications, with a Proposed Standard Specification to Cover American Rails for Export," by Albert Ladd Colby. Trans. Am. Inst. Min. Engrs., Vol. 37, p. 576 (1907). (Contains bibliography.)

Same. Iron and Coal Trades Review, Vol. 73, p. 357 (July 27, 1906).

"Rail Sections and Specifications." R. R. Gaz., Vol. 43, p. 250 (Sept. 6, 1907). (Compares rail specifications of the American Society of Civil Engineers, American Railway Engineering and Maintenance of Way Association, American Society for Testing Materials.)

"Some Progress Toward Getting Better Rails." (Editorial.) R. R. Gaz., Vol. 43, p. 577 (Nov. 15, 1907). (Brief discussion of rail specifications.)

"Proposed Standard Rail Sections of the American Railway Association." R. R. Gaz., Vol. 43, p. 627 (Nov. 22, 1907) (illustrated).

"Rail Specifications." R. R. Gaz., Vol. 43, p. 735 (Dec. 20, 1907). (Contains specifications of the American Railway Association.)

1908

"Railway Track and Track Work," p. 78; by E. E. Russell Tratman, Assoc. M. Am. Socy. C. E. Ed. 3. N. Y., 1908. Engineering News Publishing Co., 220 Broadway. $3.50 net. (Contains a comparative table of specifications for chemical composition of rails.)

Proceedings of the American Railway Association, Special Session, February 7, 1908; Regular Session, April 22, 1908, p. 359, N. Y., 1908. (Specifications for Bessemer and open-hearth steel rails, accompanying the Report of the Committee on Standard Rail and Wheel Sections, dated March 23, 1908.)

"Standard Specifications for Steel Rails." Proc. Am. Soc. for Testing Materials, Vol. 8, p. 44 (1908). (Specifications adopted Aug. 15, 1908.)

"The Present Status of Rail Specifications." R. R. Age, Vol. 45, p. 76 (Jan. 17, 1908). (A review of the action taken by the American Railway Association.)

American Society of Civil Engineers, Report of Special Committee on Rail Sections. Eng. News, Vol. 59, p. 105 (Jan. 23, 1908). (Recommended specifications for Bessemer steel rails.)

"New Steel-rail Specifications of the Pennsylvania Railroad." Eng. News, Vol. 59, p. 426 (April 16, 1908). (Gives specifications for chemical composition, process of manufacture, mechanical requirements, tests, and inspection.)

"The Pennsylvania New Rail Sections and Specifications." R. R. Gaz., Vol. 44, p. 539 (April 17, 1908).

"New Rail Sections and Rail Specifications of the American Railway Association." Eng. News, Vol. 59, p. 530 (May 14, 1908). (Specifications for Bessemer and open-hearth steel rails.)

"American Railway Association's Rail Committee." (Editorial.) Eng. News, Vol. 59, p. 533 (May 14, 1908). (Comments on the rail specifications; one and a half columns.)

"Steel-rail Breakages; Questions of Design and Specifications," by Harold V. Coes. Engineering Magazine, Vol. 35, p. 417 (June, 1908). (Gives specifications for the Union and Southern Pacific railways and British standard chemical specifications for steel rails.)

"Some Features of the Present Steel Rail Question," by Charles B. Dudley, Proc. Am. Soc. for Testing Materials, Vol. 8, p. 19 (1908). (Discusses changed demands on steel rails and proposed specifications.) Same. Engineering News, Vol. 60, p. 9.

1909

"Proceedings of the Session of the American Railway Association held in Chicago, November 17, 1909," p. 995. N. Y., 1909. W. F. Allen, Secy., 24 Park Place. (American Railway Association specifications for Bessemer and for open-hearth steel rails, adopted as recommended practice April 22, 1908.)

Proceedings Am. Ry. Eng. and M. of W. Assn., Vol. 10, Pt. 1, pp. 369, 374 (1909). (Recommended changes in specifications as previously adopted by the Association.)

" New Rail Section and Specifications, Canadian Pacific Ry." Ry. and Eng. Review, Vol. 49, p. 27 (Jan. 9, 1909). (Gives specifications for open-hearth and Bessemer rails.)

" New Rails for the Canadian Pacific Ry." (Editorial.) Ry. and Eng. Review, Vol. 49, p. 34 (Jan. 9, 1909). (Discusses specifications and rail sections.)

" New Rail Specifications of the Pennsylvania R. R. System." Eng News, Vol. 61, p. 50 (Jan. 14, 1909). (Revision of specifications of Feb. 4, 1908.)

" Pennsylvania Rail Specifications." R. R. Age Gaz., Vol. 46, p. 101 (Jan. 15, 1909). (Specifications of the Pennsylvania Railroad evised under date of Dec. 10 1908.)

" The New 85-pound Rail Section of the Canadian Pacific Ry." Eng. News, Vol. 61, p. 272 (March 11, 1909) (illustrated).

" Recent Developments in Rail Design and a Comparison of Rail Sections." (Editorial.) Eng. News, Vol. 61, p. 276 (March 11, 1909). (Compares rail specifications.)

" Recent Rail Sections." R. R. A e Gaz., Vol. 46, p. 537 (March 19, 1909) (one page, illustrated).

" New Rail Orders and Specifications." (Editorial.) R. R. Age Gaz., Vol. 46, p. 535 (March 19, 1909). (Discusses rail specifications of various railroads.)

" Rail Specifications." (Editorial.) R. R. Age Gaz., Vol. 46, p. 925 (April 30, 1909). (Very brief.)

" Rail Specifications " (letter), by R. Trimble. R. R. Age Gaz., Vol. 46, p. 1018 (May 14, 1909). (Brief letter correcting error in the above editorial.)

" Comparative Rail Specifications." R. R. Age Gaz., Vol. 46, p. 1066 (May 21, 1909). (Compares specifications of the American Railway Association, Steel Manufacturers of America, American Society of Civil Engineers, American Railway Engineering and Maintenance of Way Association, and American Society for Testing Materials, with comments.)

" Rail Sections and Specifications." (Editorial.) R. R. Age Gaz., Vol. 46, p. 1060 (May 21, 1909).

" Specifications for 90-pound Bessemer and Open-hearth Steel Rails for the Harriman Lines." R. R. Age Gaz., Vol. 47, p. 185 (July 30, 1909). (Specifications to which the Harriman Lines are ordering their 1909 rails.

" On the Question of Strengthening the Track and the Bridges with a View to Increasing the Speed of Trains Subject II, for Discussion at the Eighth Session of the Railway Congress," by M. L. Byers. Bulletin of the International Railway Congress Association, Vol. 23, p. 908 (Sept., 1909). (Gives rail specifications proposed by he American Railway Association and by the Pennsylvania Railroad Committee.)

" Report of Committee on Rail, American Railway Engineering and Maintenance of Way Association. Bulletin 118 (Dec., 1909). (Specifications for steel rails and review of previous reports.)

Abstract of same. " Specifications for Steel Rails." Railway and Engineering Review, Vol. 50, p. 118 (Feb. 5, 1910).

" Standard Specifications for Bessemer Steel Rails." Proceedings American Society for Testing Materials, Vol. 9, p. 62 (1909). (Adopted Aug. 16, 1909.)

" Standard Specifications for Open-hearth Steel Rails." Proceedings American Society for Testing Materials, Vol. 9, p. 66 (1909). (Adopted Aug. 16, 1909.)

" La Voie Courante des Chemins de Fer de l'Etat Belge," by Pierre Decamps. Revue Général des Chemins de Fer et des Tramways, Vol. 32, Pt. 2, p. 267 (Oct., 1909). (Appendix gives rail specifications of the state railroad of Belgium.)

" Revised Rail Specifications, Pennsylvania Railroad System." Engineering, Vol. 87, p. 218.

British Standard Sections, No. 47. Engineering Standards Committee (1909). (British standard specifications for bull headed and flat bottom railway rails.)

" Specifications for Standard Open Hearth Steel Rails for A. S. C. E. Sections," Carnegie Steel Co., Jan. 1, 1909. (Two leaflets.)

" Specifications for Standard Bessemer Steel Rails for A. S. C. E. Sections," Carnegie Steel Co., Jan. 1, 1909. (Two leaflets.)

" Specifications for Steel Rails." Baltimore and Ohio R. R. Co., No. 163C., Jan. 25, 1909. (Two leaflets.)

" Specifications for Open Hearth Steel Rails." Proceedings American Street and Interurban Railway Engineering Association, Vol. 7, p. 59 (1909). (Includes specifications adopted by the Transit Supply Co., Lorain Steel Co., Pennsylvania Steel Co., and the Manganese Steel Rail Co.)

1910

" Permanent Way." R. R. Engr., Vol. 31, p. 18 (Jan., 1910). (Gives Pennsylvania Railroad System specifications for steel rails.)

" Final Report of Special Committee on Rail Sections." Transactions American Society of Civil Engineers, Vol. 70, p. 456 (Paper 1177, Dec., 1910). (Contains reprint of rail specifications of the American Railway Engineering Association.)

" The American Railway Association, The American Railway Engineering and Maintenance of Way Association, Specifications for Steel Rails." Proceedings American Railway Engineering and Maintenance of Way Association, Vol. 11, Pt. 1, p. 254 (1910).

Abstracts of same. "Specifications for Steel Rails." Railway and Engineering Review, Vol. 50, p. 118 (Feb. 5, 1910). "Rail Specifications and Sections," Engineering News, Vol. 63, p. 384 (Mar. 31, 1910).

" Track Standards and General Rules." Department of Maint. of Way, Metropolitan Street Railway Co. Elec. Ry. Journal, Vol. 35, p. 863.

" Recent Work of the German Street and Interurban Railway Association." Elec. Ry. Journal, Vol. 35, p. 38. (Considers specifications and standards agreed upon.)

Hunt (Robert W.) & Co., Engineers. Bureau of Inspection, Tests and Consultation. (Includes "Specifications for Standard Open-hearth Steel Girder and High Tee-Rails," 1910, American Street and Interurban Railway Engineering Association, p. 5; and "Specifications for Standard Open-hearth Steel Girder and High Tee-Rails," Lorain Steel Co., Jan. 1, 1910, p. 14.)

1911

" Standard Specifications for Bessemer and Open-hearth Steel Rails." March 21, 1910, United States Steel Products Export Co. (Year-book, American Society for Testing Materials, 1911, p. 202.)

" Rail Sections and Specifications." Elec. Ry. Journal, Vol. 37, p. 8. (Editorial, discussing progress toward uniform specifications in 1910.)

" Interborough Rails for Tangents and Curves." Elec. Ry. Journal, Vol. 37, p. 82. (Gives recent modifications of specifications of open-hearth steel rails.)

Same, abstract, Journal of the Iron and Steel Inst., Vol. 84, p. 619.

" Manufacturers' Standard Specifications for Bessemer Steel Rails," Association of American Steel Manufacturers. Year-book, American Society of Testing Materials, 1911, p. 199.

" Specifications for Basic Open-hearth Rails," New York Central Lines. (Specifications of Oct. 1, 1909, revised Jan. 11, 1911, to conform to manufacturers' sale per 100 pounds.)

" Specifications." Report of Committee on Rail. Proceedings American Railway Engineering and Maintenance of Way Association, Vol. 12 (1911), Pt. 2, p. 12. (Gives short report of progress.)

Report of Committee A-1. Proceedings American Society for Testing Materials (1911), Vol. XI, p. 48. (Contains reference to international specifications for rails.)

1912

" Specifications for Carbon Steel Rails." Proceedings American Railway Engineering Association (1912), Vol. 13, p. 565.

" New Specifications for Steel Rails." Iron Age, Vol. 89, p. 816. (Gives report of rail committee at 1912 meeting of the American Railway Engineering Association and specifications adopted.)

" Specifications for 85-pound and 100-pound Carbon Steel Rails," 1912, Pennsylvania Railroad Company. (Two leaflets.)

" Specifications for Standard Bessemer Steel Tee Rails," 1912 Catalogue, Maryland Steel Company, p. 10.

" Specifications for Standard Open-hearth Steel Tee Rails," 1912 Catalogue, Maryland Steel Company, p. 12.

" Specifications for Standard Open-hearth Steel Girders and High Tee Rails," 1912 Catalogue, Pennsylvania Steel Company, p. 14.

APPENDIX

REPORTS AND RECORDS

THE forms recommended by the Rail Committee of the American Railway Engineering Association, and contained in the 1911 Manual of the Association, are typical of the best practice, and are shown on Figs. 342 to 359 inclusive and Plate XXXIII. The explanation of the forms as given by the committee is as follows:

GROUP I. REPORTS OF RAIL INSPECTION AND SHIPMENT AT THE MILL

This set of forms, Figs. 342–344 and Plate XXXIII, is for the use of the railroad company's Inspector at the mills where the rail is rolled, and gives all the information necessary to inform the purchaser that his order has been manufactured in accordance with the specifications and shipped.

A. B. & C. R. R. Co.

Report of Chemical and Physical Examination

Sheet No.______
of______Sheets

of________ Rails ____________________ Process__________ lbs. per yd.________Section
No. (Open Hearth, Bessemer or Special)

Manufactured by__________________Steel Co., at______________________Works

For ____

Order No. ________ Date of Report ________________19____

No. of Passes in Rolls__________ Bar held on average of________seconds at__________Pass.

Shrinkage Allowance at Saws____________inches on 33-ft. rails

Distance between supports on Straightening Press____________________

Weight of Tup, 2000 lbs. Height of Drop __________ft Distance between Supports, 3 ft

Average Number of Rails per Heat ____

Heat No.	Percentage of Crop from Ingot. No. of Ingots	% from Top	% from Bottom	Carbon.	Manganese.	Phosphorus.	Silicon.	Sulphur			Drop Test Deflection Inches.	Remarks
												1
												2
												3
												4
												5
												6
												7
												8
												9
												10
For	filling in	with ty	pewriter	columns	should	be spaced	in tenths of	an inch	as given	by the figures		11
7	4	5	5	5	5	5	5	5	5	5	5	11 12
				Size of	sheet required,	8x10½	inches.					13
												14
												15
												16
												17
												18
												19
												20
												21
												22
												23
												24
												25
												26
												27
												28
												29
												30
												31
												32

Note—Requirements of Standard Specifications are to be stated on line 1

Instructions

One copy of this report to be forwarded to the Chief Engineer M of W

Correct ____________________________
Inspector

Approved ____________________________
Chief Inspector
Engineer of Tests

FIG. 342.

M. W. 401. — Report of Chemical and Physical Examination:

This blank is filled out from the mill records under the supervision of the Inspector, and gives the chemical contents taken from the ladle analysis and the result of the drop test.

A. B. & C. R. R. Co.

No.________

CERTIFICATE OF INSPECTION

of________________ Process Rails__________lbs. per yd.________________ Section.
(Open Hearth, Bessemer or Special)

Manufactured by________________________Steel Co. at__________________Works

For____

Mr.________________________Chief Engineer M. of W. Date______________19___

The following Steel Rails have been inspected and accepted according to contract.

Rails are certified to be within the limits of the Specifications of the__________________

____

and approved as per details given below.

All Rails have been inspected and approved for Chemical Analysis, Physical Tests, Section, Weight, Straightening, Drilling, Sawing, Length, Stamping, Finish, Quality.

All Rails are marked on the web with maker's name, date of manufacture, Heat Number, and position occupied in the ingot. Date of Rolling__________________

No. of Rails Rolled________________ No. of Rails Accepted________________

No. of Rails temporarily rejected and cause________________________________

____

____

No. of Rails condemned and cause____

____

____

For filling in with typewriter columns should be spaced in tenths of an inch as shown by the figures under columns. Size of sheet required, 8x10½ inches.

This Certificate covers the run from

Heat No.__________ to Heat No.__________both inclusive

Number of Rails of each Length.

Length		33	30		27½		25		Total.
Number									
7	6	6	5	4	4	4	4	4	6

8

Calculated Weight.			Shipper's Scale Weight.		
Total Pounds	Tons	Pounds	Total Pounds	Tons	Pounds
11	7	7	11	7	7

8

Amount accepted under this Certificate__________________

Total amount of Order__________________________

Balance due on Order__________________________

Trial Weights

Hours	Wts.	Hours	Wts.
6 A		6 P	
7 "		7 "	
8 "		8 "	
9 "		9 "	
10 "		10 "	
11 "		11 "	
12 M		12 M	
1 P		1 A	
2 "		2 "	
3 "		3 "	
4 "		4 "	
5 "		5 "	
5	6	5	6

Instructions

One copy of this Certificate is to be made out and forwarded to the Chief Engineer M. of W. of the Railway Company.

Correct.____________________________
Inspector.

Approved:____________________________
Chief Inspector
Engineer of Tests.

FIG. 343.

M. W. 402. — Certificate of Inspection:

This is the Inspector's written statement that the material which he has witnessed rolled has been turned out strictly in accordance with the specifications and the order of the railroad company.

Copy Ink.

A. B. & C. R. R. Co.

No.-----

REPORT OF SHIPMENT.

of ________________ Process Rails _________lbs. per yd __________Section
(Open Hearth, Bessemer or Special.)

Manufactured by ____________________Steel Co. at ________________Works.

for ____

Consigned to ____

Order No. ______________ Date of Report __________________19__

Quality No. _____________ Sheet No _____of____Sheets.

	Loaded on Cars.		Number of Rails of each Length.									Shipper's Weights
	Initial	No		33	30		27½		25		Total Rails	Pounds
1												
2												
3												
4												
5												
6												
7												
8												
9												
10												
11												
12												
13												
14	For filling in with typewriter columns should be spaced in tenths of an inch as given by the figures.											
8 15	9	9	5	5	5	5	5	5	5	5	6	8
16					Size of sheet required 8x10½ inches							
17												
18												
19												
20												
21												
22												
23												
24												
25												
26												
27												
28												
29												
30												
31												
32												
		Totals										
	Total Weight Expressed in Gross Tons and Decimals.											

Total Tons of Order______Tons previously shipped_____ Balance due __________

INSTRUCTIONS

One copy of this report is to be sent to the Chief Engineer M. of W., and two copies to the General Superintendent, one of which is for the Division Superintendent

Correct ______________________
Inspector.

Approved ______________________
Chief Inspector.
Engineer of Tests

FIG. 344.

M. W. 403. — Report of Shipment:

This blank is used for reporting the number and length of rail shipped in each car from the works, and, when properly checked by the Receiving Officer, it furnishes the basis for payment of the bill.

M. W. 418. — Results of Drop Tests and Surface Inspection of Rails Rolled (Plate XXXIII).

This form is intended for tabulating the results of drop tests and surface inspection of rails rolled.

Group II. Reports from Division Officers

This group, Figs. 345–347, contains all the regular reports which come from the division officers concerning the rails which have been put in service in track.

A. B. & C. R. R. Co.

No..................

......................Division.......................Branch.

Report of RAIL FAILURES in Main Tracks

Section No..........   Date of Report...........................191...

1	Weight per yard, New..............lbs Re-rolled ....lbs.	16	Was Rail much or little worn?.......
		17	By whom discovered.................
2	Rail Section?........................	18	Date and Time found?...............
3	Brand on Rail? ("D" on back)........	19	Was Rail removed?................ Date removed?...................
4	Kind of Steel? ("E" on back)........		
5	Heat No. on Rail? ("F" on back)......		
6	Rail No. or Letter? ("F" on back)....	20	Exact gage of Track at "Break"?.....
7	Original Length of Rail?............	21	Was "Break" over or between Ties?..
8	Month and Year Rail was Laid........	22	Was "Break" square or angular?.....
9	Location ....Feet ....of Mile Post	23	Distance between edges of Ties at "Break?" ....
10	Which Track?....................... Which Rail?	24	Condition of Ties each side of "Break?" ....
11	On Curve or Straight Line?...........	25	Kind of Ties?.......................
11½	No. of Curve?.......................	26	Were Tie Plates used?.............. Kind?...........................
12	Degree of Curve?...................		
13	High or Low Rail, if on Curve?.......	27	Condition of Line and Surface?......
14	Superelevation of Curve at "Break"?..	28	Kind of Ballast?...................
		29	Was Track properly ballasted?.......
15	Was Rail "Broken"?................... or "Defective"?................... or Damaged?..................... (See "Description of Failures" on back)	30	Kind of material in roadbed under ballast? ....
		31	Was Track well drained?............
		32	Was Roadbed frozen?...............

33 Condition of weather? (Wet, dry, warm or cold, freezing or thawing)............

34 If "Broken," state cause of break, and describe any flaws found at point of break ....

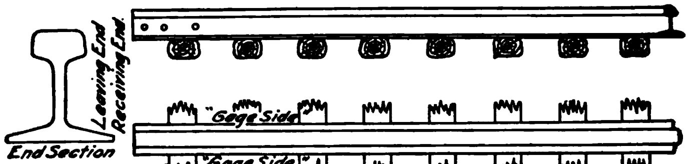
35 If "Break" was at joint, state kind, number of holes, and whether it was full bolted or insulated..

36 Were any bolts at joint loose?...................If so, how many?...........

37 Was accident or detention to trains caused by "Break"?........................ If so, state circumstances..

38 If "Defective," describe kind and location of flaws or defects, and if possible, what caused them. (See "Description of Failures" on back).................. ....

39 Draw on Diagram lines of "Break," or partial fracture, such as long pieces from side of head and half-moon pieces from base, showing dimensions. Hollows in head should be shown on "End Section." Defects may also be indicated on Diagram. Mark distance from end to "Break." *If "Break" is nearest "Receiving End," draw pen through words "Leaving End;" if nearest "Leaving End," draw pen through words "Receiving End." (*Refers to track upon which the current of traffic is in one direction.) Indicate "Gage Side" on "Diagram" below, by drawing pen through words "Gage Side" on opposite side.



40 If "Damaged," describe nature and cause if known. (See "Description of Failures" on back)..

Correct: Approved:

............................Foreman.   ....Supervisor.

Instructions, and Description of Failures, on Back.

Fig. 345. (Face of Form.)

M. W. 404. — Report of Rail Failures in Main Tracks:

This is the basic report of all rail failures and is sent by the Track Foreman to his Supervisor and by him transmitted to the Division Engineer. It contains a classification of rail failures which is used in the tabulations employed in the following blanks.

INSTRUCTIONS

A. The Foreman will send this Report to the Supervisor the same day the break is discovered, and in the case of a damaged or defective rail, the day it is taken out of the track.

B. The Supervisor will forward this Report direct to the Division Engineer.

C. The Division Engineer will have copies of this Report made immediately upon receipt and send a copy to the Chief Engineer M. of W.

D. The answer to 3 is in raised characters on the web of the rail.

E. The answer to 4 is "Bessemer" (B); "Open-Hearth" (O.H.); "Nickel" (N.); "Ferro-titanium (F.T.); "Chrome Nickel" (C.N.); or other method of manufacture or alloy.

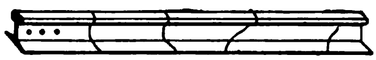
F. The answers to 5 and 6 are stamped into the metal on side of web—figures for 5 and a letter for 6.

G. Mile Post No. from $\left\{\begin{matrix}\text{South}\\ \text{East}\end{matrix}\right.$ end of Division to be used.

DESCRIPTION OF RAIL FAILURES

When describing Failures of Rails, the following terms should be used.

1. **Broken Rail.** This term is to be confined to a rail which is broken through, separating it into two or more parts. A crack which might result in a complete break will come under this head.



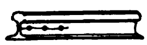
DEFECTIVE.

2. **Flow of Metal.** This term means a "Rolling Out" of the metal on top of the head towards its sides without there being any indication of a breaking down of the head structure, that is, the under side of the head is not distorted.

3. **Crushed Head.** This term is used to indicate a "Flattening" of the head, and is usually accompanied by a crushing down of the head as shown in sketch.

4. **Split Head.** This term includes rails split through or near the center line of the head, or rails with pieces split off the side of the head. When this term is used it should be further defined by stating whether it is or is not accompanied by a seam or hollow head.

5. **Split Web.** This term is a longitudinal split along the axis of the web, generally starting from the end of rail through the bolt holes.



6. **Broken Base.** This term covers all breaks in base of rail and should be described and illustrated on sketches on front page.

7. **Damaged.** Under this head will be included all rails broken or injured by wrecks, broken wheels or similar causes.

Fig. 345 (continued). (Back of Form.)

A. B. & C. R. R. Co.

Sheet No . . ...of......Sheets.

______________ Division.

Superintendent's Report of **Rail Failures** in Main Track for the Month of______________19____

Report Number	Description of Rail									Location of Rail					Date Laid		Day of Month Found	Time in Service		Nature of Failure							In Splice	Out of Splice	Line No.
	Weight per Yard	Type of Section	Marks on Rail: Manufacturer	Marks on Rail: Rolled Mo.	Marks on Rail: Rolled Year	Marks on Rail: Kind of Steel	Marks on Rail: Heat No.	Marks on Rail: Rail Letter	Lengths	Mile Post No.	Mile Post Feet	Which Track	Curve or Tangent	Degree of Curve	Mo.	Year		Year	Mos.	Damaged	Broken	Flow of Metal	Crushed Head	Split Head	Split Web	Broken Base			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	
																													1
																													2
																													3
																													4
																													5
																													6
																													7
																													8
																													9
																													10
																													11
																													12
																													13
																													14
																													15
																													16
																													17
																													18
																													19
																													20
																	Total Failures												

Grand Total of Failures for Month

In Column
In Column
" "
Entries in

olumns:
Works.
Mar for Maryland.
C. for outer rail on Curve.
umn.
29.
Instructions on back.

Correct.
.... Division Engineer
Approved.
. . .. Superintendent

FIG. 348. (Face of Form.)

M. W. 405. — Superintendent's Monthly Report of Rail Failures in Main Tracks:

On this blank the Division Engineer informs his Superintendent of the total number of rail failures for the month, tabulated from the Track Foreman's

INSTRUCTIONS

A. The Division Engineer will make out two copies of this report at the end of the month from the Section Foremen's Reports, and send one copy to the Chief Engineer M. of W. and one to the General Superintendent.

B. Mile Post No. from $\left\{\begin{matrix}\text{South}\\\text{East}\end{matrix}\right.$ end of Division to be used.

DESCRIPTION OF RAIL FAILURES

When describing Failures of Rails, the following terms should be used:

1. **Broken Rail.** This term is to be confined to a rail which is broken through, separating it into two or more parts. A crack which might result in a complete break will come under this head.

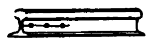
DEFECTIVE.

2. **Flow of Metal.** This term means a "Rolling Out" of the metal on top of the head towards its sides without there being any indication of a breaking down of the head structure, that is, the under side of the head is not distorted.

3. **Crushed Head.** This term is used to indicate a "Flattening" of the head, and is usually accompanied by a crushing down of the head as shown in sketch.

4. **Split Head.** This term includes rails split through or near the center line of the head, or rails with pieces split off the side of the head. When this term is used it should be further defined by stating whether it is or is not accompanied by a seam or hollow head.

5. **Split Web.** This term is a longitudinal split along the axis of the web, generally starting from the end of rail through the bolt holes.



6. **Broken Base.** This term covers all breaks in base of rail and should be described and illustrated on sketches on front page.

7. **Damaged.** Under this head will be included all rails broken or injured by wrecks, broken wheels or similar causes.

Fig. 346 (continued). (Back of Form.)

report, and other officers who are interested, such as the Chief Engineer, Chief Engineer of Maintenance of Way, or General Superintendent, are furnished with copies. In cases where a copy of the Track Foreman's report is sent to the Chief Engineer or Chief Engineer of Maintenance of Way, the monthly report serves as a check on the receipt of all individual rail reports.

A. B. & C. R. R. Co.

______________________________Division.

Statement of Steel Rails existing in Main Tracks of______________________________Division.

_______________Main Track. December 31, 19___.

Location.				Year Laid.	Brand.	Weight per Yard.	Type of Section.	Length of Feet in Track			
From		To						Laid Previous to 19	New Steel Laid 19	Steel Laid 19	Remarks.
M.P.	+ft.	M.P.	+ft.					1	2	3	4
For filling in with typewriter columns should be spaced in tenths of an inch as given by the figures.											
4	5	4	5	3	12	4	5	8	7	7	16
Size of sheet required 8 inches wide.											

No. ft. 60 lb. Rail	No. Tons
" " 70 " "	" "
" " 85 " "	" "
" " 100 " "	" "

Column 3 to be used for any special rail, such as Re-rolled or Sawed and Re-drilled.

To be made out and forwarded by the Engineer M. of W. to the Chief Engineer M. of W., as soon after the close of the year as possible.

Correct:

Engineer M. of W.

Fig. 347.

M. W. 406. — Annual Statement of Steel Rails Existing in Main Tracks: This is an annual report sent by the Division Engineer to the Chief Engineer or Chief Engineer of Maintenance of Way, for the permanent record of the company, to show the different kinds of steel in the main tracks at the end of the year. This may be used in conjunction with the rail chart, or take its place altogether, because the rail chart may not be in convenient form for a permanent record, which may be referred to, after many years, for information concerning the kind of rail in use at a stated period.

Copy Ink
Report No.

A. B. & C. R. R. Co.

Laboratory Report of Chemical and Physical Examination of Rail and Other Track Material.

Referred to in--

Laboratory No.----------Sample represents--

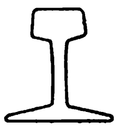
Place and Date-------------------------19---

Location of Borings	C.	P	Mn	Si	S						Tensile S'gth Pounds Per Square Inch	Elastic Limit Pounds Per Square Inch	Elongation Per Cent in . Inches	of Or. Lth.	Reduc. of Area, % of Orig. Sec.		
	Chemical Analysis.										Physical Test.						
11	5	5	5	5	5	5	5	5	5	5	7	7	6	6	6	6	6

For filling in with typewriter columns should be spaced in tenths of an inch as given by the figures.

Size of sheet required, 8x10½ inches

Location of Borings



Remarks.

Approved --------------------------------
Chemist
Engineer of Tests.

Note The word "Borings" refers also to "Chippings" and other kinds of test fragments

FIG. 348. — M. W. 407. — Laboratory Examination of Special Rails.

Group III. Laboratory Examination of Special Rails

This group is, at present, represented by the single form shown in Fig. 348. It is used for making check analyses against the mill analyses and for reporting the result of chemical analysis and physical test of special rail or other test pieces which may be sent to the laboratory, from time to time, for examination. Fig. 349 shows standard locations of borings for chemical analyses and also the standard tensile test pieces of the association.

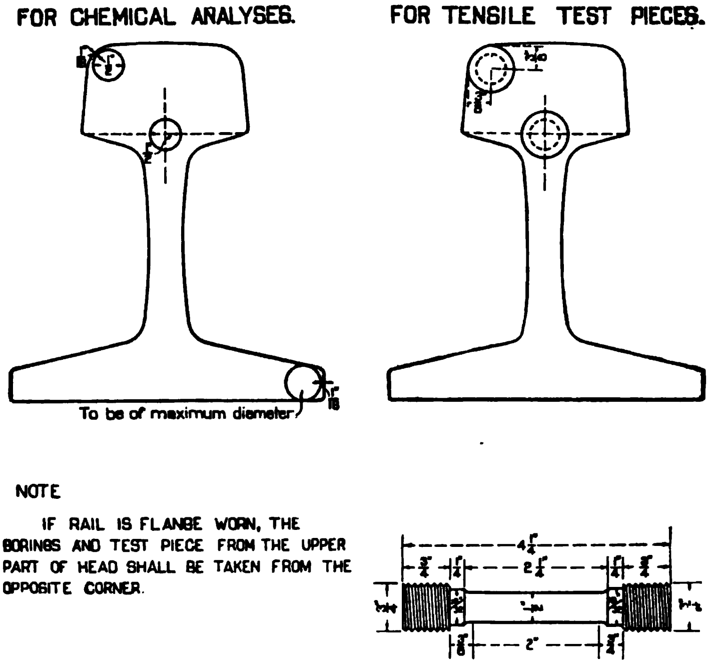


Fig. 349. — Standard Locations of Borings for Chemical Analyses and Standard Tensile Test Pieces.

Group IV. Compilation of Results for Study

This group, Figs. 350–354, exhibits the different ways for compiling quantitative statistics of rail failures.

M. W. 408 (Fig. 350) is intended for compiling the information relative to rail failures for a period of one year.

The columns for "specified chemical analysis" are intended for recording the analysis of the particular lot of rail as given in the specification, and is inserted in this blank in order to give an idea as to whether the rail is high or low in carbon, or high or low in phosphorus, etc.

M. W. 409 (Fig. 351) has been provided on which the results from M. W. 408 will be recorded at the end of the year, thus making a continuous record.

Enter under the head of "Tons Laid" all Kinds of Rail, with names of Manufacturers and Sections, which are in the Main Tracks, whether or not there have been failures.

A. B. & C. R. R. Co.

RAILROAD

Summary of Steel Rail Failures for One Year Compared with same Period of Previous Year

_____ lb. _____ Sec. _____ Steel. Rolled by _____ Steel Co. Record for Period of One Year ending October 31, 19__

DIRECTIONS FOR FILLING IN THIS BLANK.

1. Enter on each sheet as many kinds of rail as the sheet will hold, and give the weight, section, kind of steel and manufacture of each group.
2. Foot up the columns of each group.
3. If failures are reported for years during which tons of "new rail laid" are not given, such failures should be footed separately from the failures of years during which tons of "new rail laid" are given.
4. Give the "gross tons over rail" for the year covered by this blank only, and enter it on the total line.
5. Give the number of failures (per 10,000 tons of rail laid) during the last year and the present year in whole numbers and tenths.

Lines	Year Laid	Tons of New Rail Laid Even Tons	Specified Chemical Analysis C.	P	Mn	Si	S		Maximum Axle Load of Locomotives Freight Pounds	Passenger Pounds	Gross Tons over Rail Millions and Tenths		Kind of Failure: Broken Tang.	Broken Curve	Flow of Metal Tang.	Flow of Metal Curve	Crushed Head Tang.	Crushed Head Curve	Split Head Tang.	Split Head Curve	Split Web Tang	Split Web Curve	Broken Base Tang	Broken Base Curve	Total Tang.	Total Curve	Grand Total	Failures per 10,000 Tons of New Rail Laid Last Year	Present Year	Lines
1												%																		1
												No.																		
2												%																		2
												No.																		
3												%																		3
												No.																		
4												%																		4
												No.																		
5												%																		5
												No.																		
6												%																		6
												No.																		
7												%																		7
												No.																		
8												%																		8
												No.																		
9												%																		9
												No.																		
10												%																		10
												No.																		
11												%																		11
												No.																		
12												%																		12
												No.																		
13												%																		13
												No.																		
14												%																		14
												No.																		
15												%																		15
												No.																		
16												%																		16
												No.																		
17												%																		17
												No.																		
18												%																		18
												No.																		
19												%																		19
												No.																		
20												%																		20
												No.																		
21												%																		21
												No.																		

NOTE—Only statistics of Rails weighing over 70 lbs. per yard are required. Rails broken or injured by wrecks, broken wheels or similar causes, are not to be included in this report.

(513) FIG. 350.—M. W. 408.—Summary of Steel-rail Failures for One Year Compared with the Same Period of Previous Year.

_______________________Railroad

Summary of Steel Rail Failures for a Period of Years

Record for period of________years ending__________19___

______lb.______Section________Steel. Rolled by__________Steel Co.

Lines	Year Laid	Tons of New Rail Laid	Number of Rails which have failed each year below.																Kind of Failure: Broken		Flow of Metal		Crushed Head		Split Head		Split Web		Broken Base		Total		Grand Total	Failures per 10,000 tons new rail laid	Lines
																			Tang.	Curve	Tang.	Curve	Tang.	Curve	Tang.	Curve	Tang.	Curve	Tang.	Curve	Tang.	Curve			
																		%	2																
1																		No.	2																1
																		%	2																
2																		No.	2																2
																		%	2																
3																		No.	2																3
																		%	2																
4																		No.	2																4
																		%	2																
5																		No.	2																5
																		%	2																
6																		No.	2																6
																		%	2																
7																		No.	2																7
																		%	2																
8	5	7	5	5	5	5	5	5	5	5	5	5	5	5	5	5		No.	5 2	5	5	5	5	5	5	5	5	5	5	5	5	5	7	5	8
																		%	2																
9																		No.	2																9
																		%	2																
10																		No.	2																10
																		%	2																
11																		No.	2																11
																		%	2																
12																		No.	2																12
																		%	2																
13																		No.	2																13
																		%	2																
14																		No.	2																14
																		%	2																
15																		No.	2																15
																		%	2																
16																		No.	2																16
																		%	2																
17																		No.	2																17
																		%	2																
18																		No.	2																18
																		%	2																
19																		No.	2																19
Totals																																			

For filling in with typewriter columns should be spaced in tenths of an inch as given by the figures:

Size of sheet required, 8 x 21 inches.

NOTE—Rails broken or injured by wrecks, broken wheels or similar causes, are not to be included in this report.

FIG. 351.—M. W. 409.—Summary of Steel-rail Failures for a Period of Years.

A. B. & C. R. R. Co.

Sheet No..........of..........Sheets.

..............................Division

Comparative Number of Failures of Steel Rails of Different Section or Pattern Rolled by Different Steel Companies.

Record for Period of..........................ending..........................19......

Steel Company and Mill where Rail was Rolled	Rail weight per yard, lbs.	Rail Section or Pattern	No. of Tons of Rail laid in Track	Kind of Failure: Broken, Tan.	Broken, Curve	Flow of Metal, Tan.	Flow of Metal, Curve	Crushed Head, Tan.	Crushed Head, Curve	Split Head, Tan.	Split Head, Curve	Split Web., Tan.	Split Web., Curve	Broken Base, Tan.	Broken Base, Curve	Total, Tan.	Total, Curve	Grand Total	No. of Failures per 10,000 Tons of New Rail Laid
10	4	5	7	4	4	4	4	5	4	5	4	4	4	4	4	5	5	7	5

For filling in with typewriter columns should be spaced in tenths of an inch as given by the figures:

Size of sheet required, 8x10½ inches.

Note: The percentages which the record figures are of the total are to be put above the record figures in the several columns under "Kind of Failure."

Fig. 352.

M. W. 410. — Comparative Number of Failures of Steel Rails of Different Section or Pattern, Rolled by Different Steel Companies:

In order to compare the product of different mills, and also to compare different weights per yard and different sections together, this blank has been provided. It contains the totals taken from M. W. 408 or M. W. 409 as desired.

A. B. & C. R. R. Co.

______________________________ Division

Position in Ingot of Steel Rails which Failed
for Period of__________ ending_______ 19___

Sheet No.______ of______ Sheets

__________________ Type of Rail Section

Kind of Failure	__Steel Co.______Mill______Steel								___Steel Co._____Mill____Steel								__Steel Co._____Mill_____Steel								____Steel Co._____Mill_____Steel							
	lb.								lb.								lb.								lb.							
	A	B	C	D	E	F	Un-known	Total	A	B	C	D	E	F	Un-known	Total	A	B	C	D	E	F	Un-known	Total	A	B	C	D	E	F	Un-known	Total
Broken																																
Flow of Metal																																
Crushed Head																																
Split Head																																
Split Web																																
Broken Base																																
Totals																																
	Steel Co._____Mill_____Steel								Steel Co._____Mill_____Steel								Steel Co._____Mill_____Steel								___Steel Co._____Mill_____Steel							
Broken																																
Flow of Metal																																
Crushed Head																																
Split Head																																
Split Web																																
Broken Base																																
Totals																																
	__Steel Co._____Mill_____Steel								___Steel Co._____Mill_____Steel								___Steel Co._____Mill_____Steel								____Steel Co._____Mill_____Steel							
Broken																																
Flow of Metal						For filling in with typewriter columns should be spaced in tenths of an inch as given by the figures:																										
13 Crushed Head	4	4	4	4	4	4	5	5	4	4	4	4	4	4	5	5	4	4	4	4	4	4	5	5	4	4	4	4	4	4	5	5
Split Head													Size of sheet required, 8x15 8/10 inches.																			
Split Web																																
Broken Base																																
Totals																																

Note The letters A, B, C, etc., denote the position of the Rail in the ingot, "A" being the top rail, "B" the second, etc.
The percentages which the record figures are of the total are to be put above the record figures in the columns under A, B, C, etc.,
Only Statistics of Rail weighing over 70 lbs. per yard are required.

FIG. 353.

M. W. 411. — Position in Ingot of Steel Rails which Failed:

This is intended to furnish data on the number and character of rail **failures** according to the original position in the ingot held by the rail in question.

(Cover Page for Forms M. W. 408, 409, 410, 411.)

A. B. & C. R. R. Co.

______________________________Division

Numerical Record and Position in the Ingot of Steel Rails which have Failed in Service.

on______________________________

Year____________________ to Year 19_____

Office of CHIEF ENGINEER M. of W.
(or other officer)

Fig. 354.

M. W. 412:

The information in this group should be bound together in one book; this cover has been provided for convenience and neatness.

Group V. Progressive Wear of Special Rail under Observation

In order to keep track of special rail, from time to time, and determine the value of the results being given, it is necessary to have a systematic plan of procedure for examinations and records. This group, Figs. 355–359, is furnished for that purpose, and is provided with a cover, as in the case of the previous group.

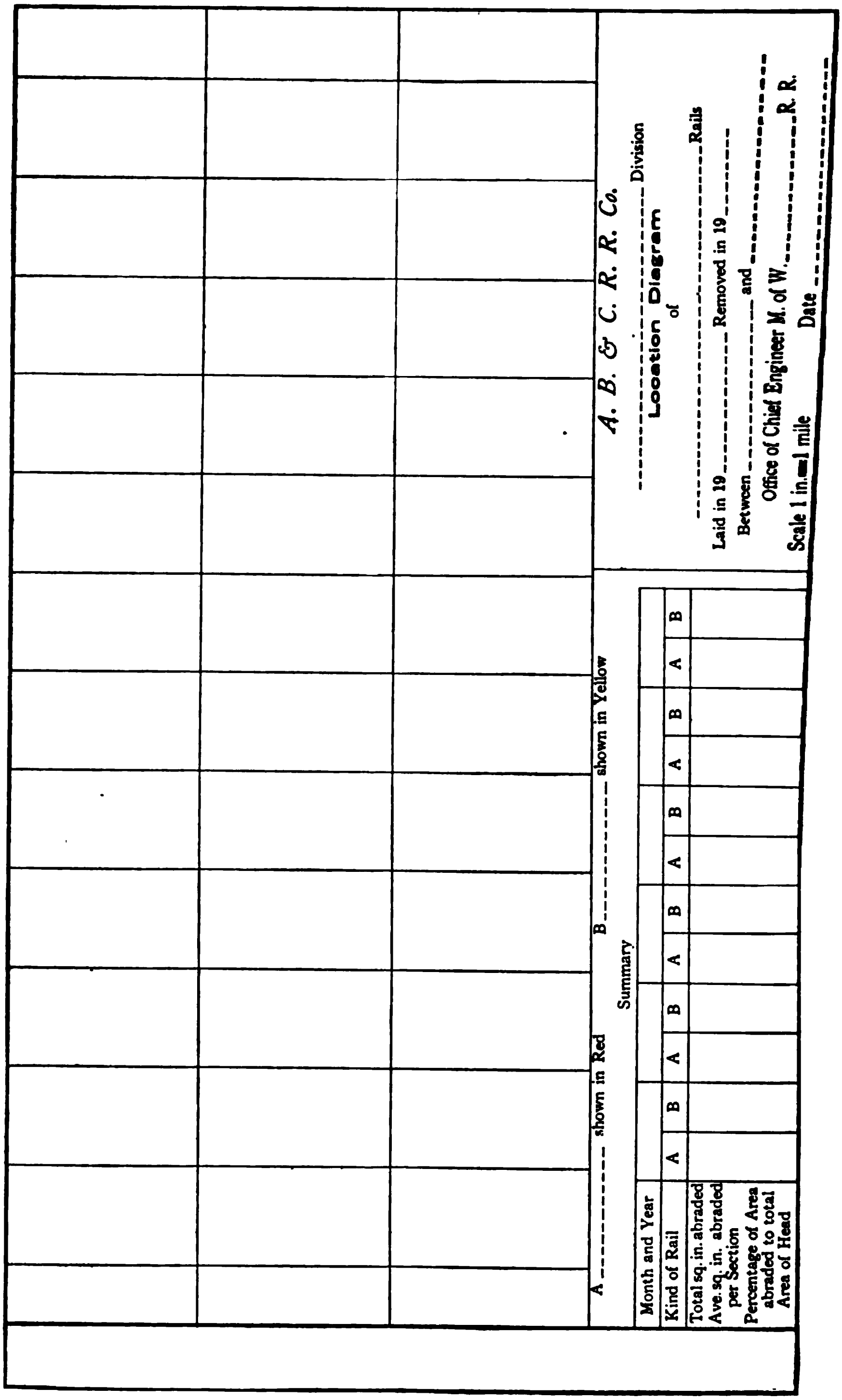


Fig. 355.

M. W. 413. — Location Diagram:

This blank is on a scale one inch equals one mile, and is intended for diagrams showing the location in different places of the same kind of rail under trial.

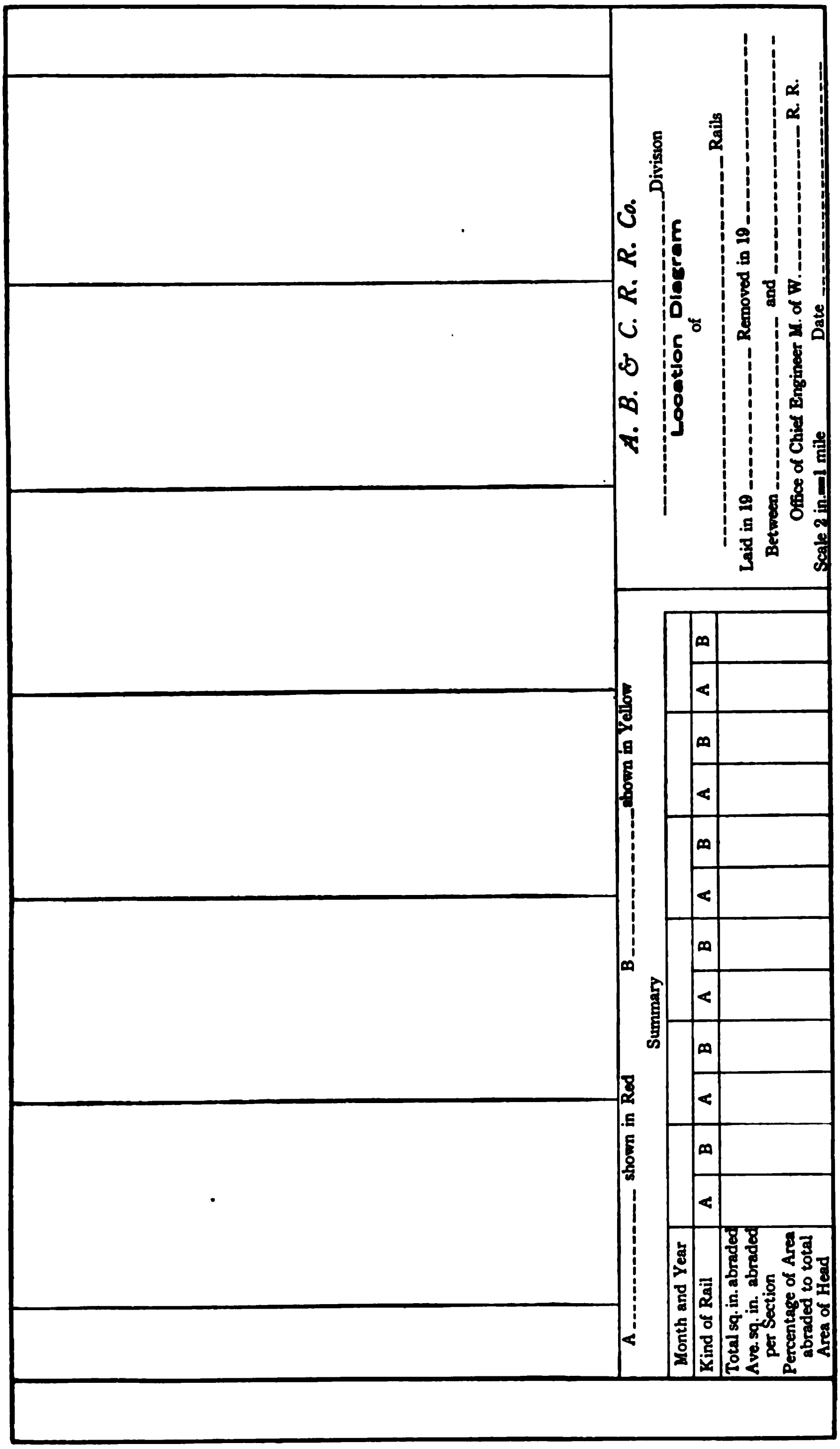


FIG. 356.

M. W. 414. — Location Diagram:

This is similar to M. W. 413 except that it is on a scale of two inches equal one mile, and is intended to show the location of a particular portion of the rail given in M. W. 413. It is made on a larger scale, so as to locate the points of measurement. A place is provided on each blank for the summary of the wear or area abraded in percentage of total area of head.

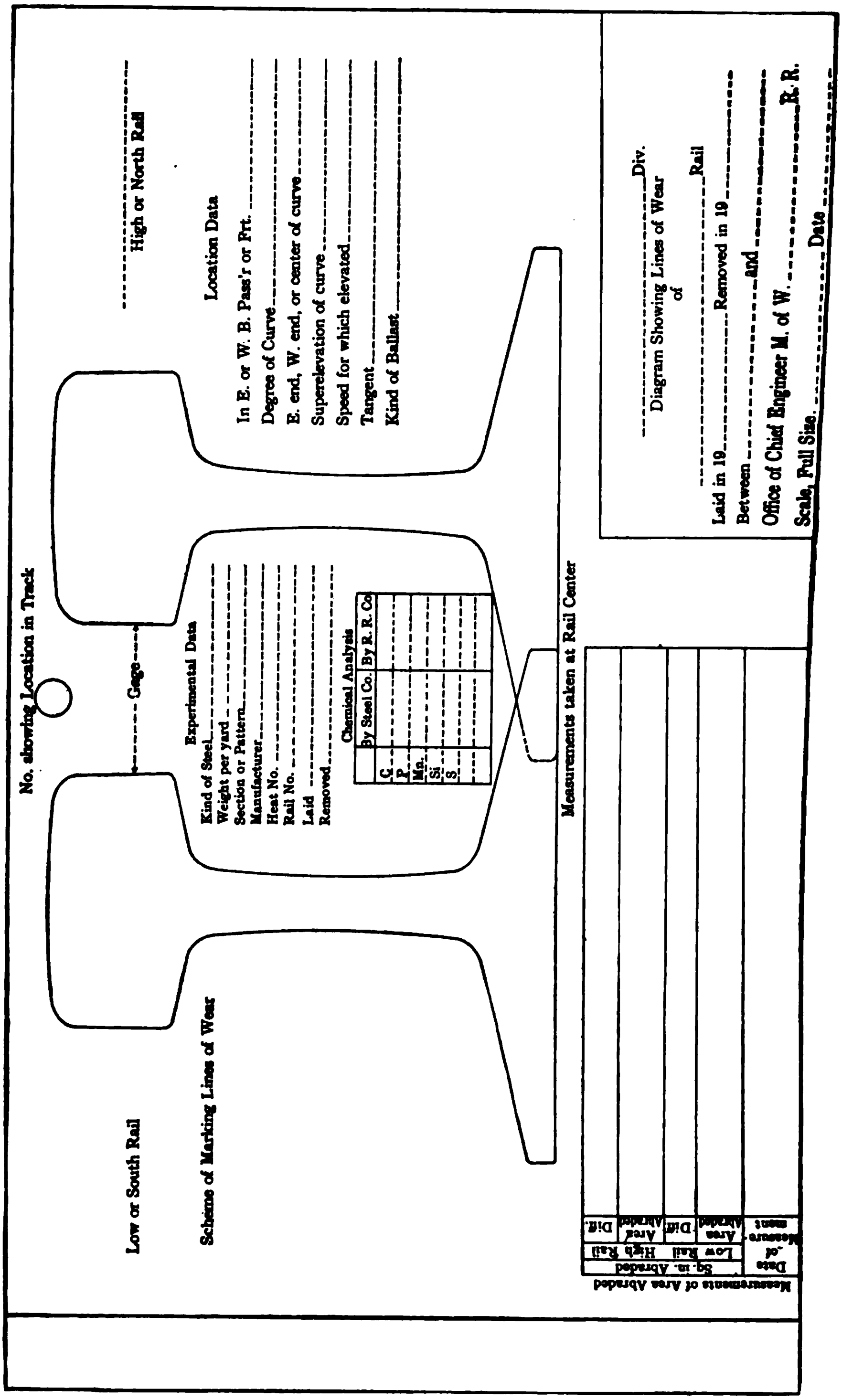


FIG. 357.

M. W. 415. — Diagram Showing Lines of Wear:

The measurement of rail section at a specified point is shown on this blank and its position on M. W. 414 is given by the number in the circle of the blank at the top. All statistical information of interest and importance is given on the blank.

A. B. & C. R. R. Co.

__________________ Division

Record of Comparative Wear of Special Rail

Date of Report ________________________ 19____

Special Rail												Chemical Composition of Rail of Section with which Special Rail was Compared						Special and Comparative Rails						
Kind of Steel	Location	No. of Tons Laid	Weight per yard	Type of Section	Manufacturer	Chemical Composition												Date Laid	Date Removed	Length of Service at date of Report	Average Area Abraded of all the Sections taken			
																					Special		Comparative	
						C	P	Mn	Si	S		C	P	Mn	Si	S					Sq. in. abraded	% of area of Head	Sq. in. abraded	% of area of Head
12	14	6	5	6	10	4	4	5	4	4	4	4	4	5	4	4	4	6	6	6	5	5	5	5

For filling in with typewriter columns should be spaced in tenths of an inch as shown by the figures.

Size of sheet required, 8x15 4/10 inches.

Note: Only Statistics of Rails weighing over 70 lbs. per yard are required.

FIG. 358.

M. W. 416. — Record of Comparative Wear of Special Rail:

This blank is intended for compiling the information given in the previous ones, so as to give a general summary of the results.

(Cover Page for Forms M.W. 413, 414, 415, 416.)

A. B. & C. R. R. Co.

________________________Division

RAIL SECTIONS

Showing Progressive Wear
of

________________and________________Steel Rails.

Laid________________ Removed________________

Office of CHIEF ENGINEER M. of W.
(or other officer)

FIG. 359.

M. W. 417:

The information in this group should be bound together in one book; this cover has been provided for convenience and neatness.

In some cases it may prove desirable to use charts or diagrams which illustrate graphically the information found in the records. The diagrams of rail failures found in the Proceedings of the American Railway Engineering Association are examples of this. Fig. 360 shows a method of recording the failures of different groups of rails during a period of years, and shows as well the distribution of the failures during each year. It will be noted from the figure that the rails failed, with a few exceptions, during the winter and spring months. A modification of this diagram can be obtained by making the record cumulative, which affords a ready comparison of the behavior of different rollings after having been in service any considerable length of time.

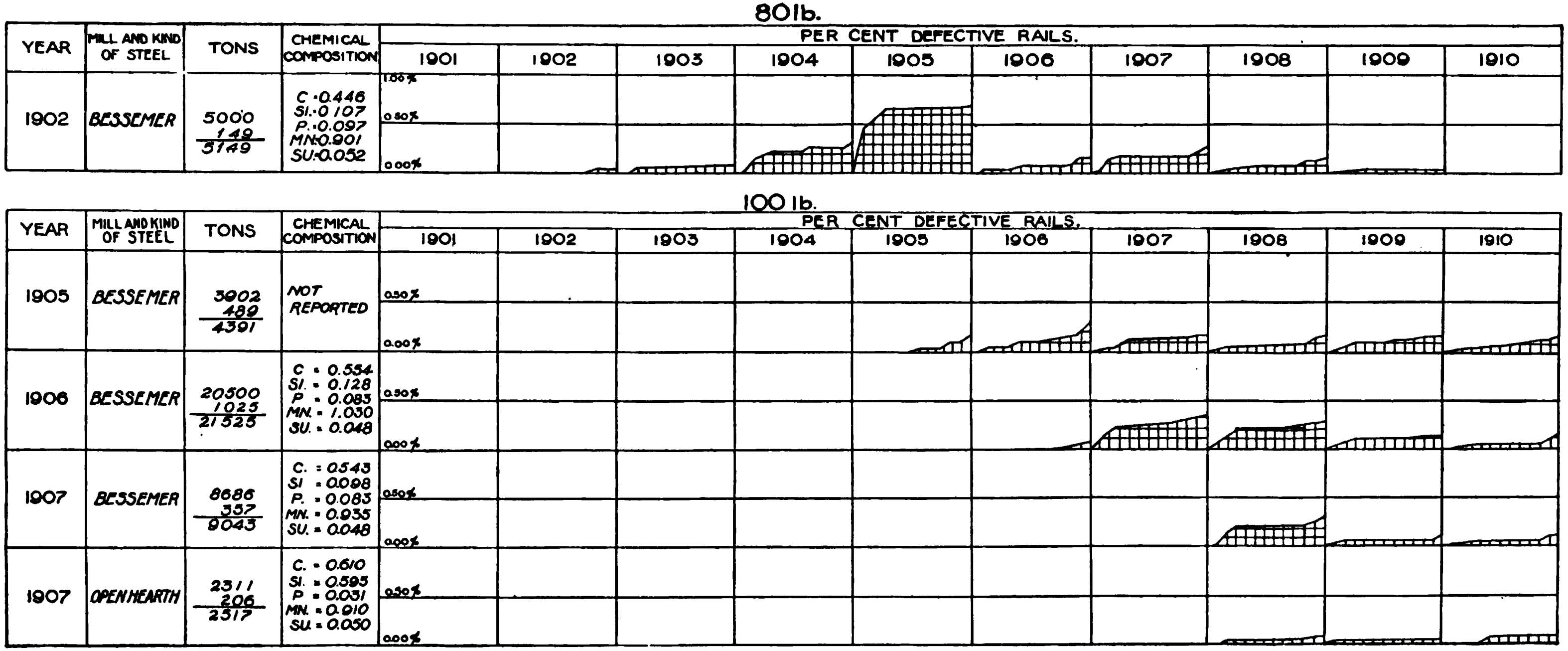


FIG. 360. — Defective Rail Sheet.

Fig. 361 presents a further example and shows a diagram of rail failures on the Harriman Lines.

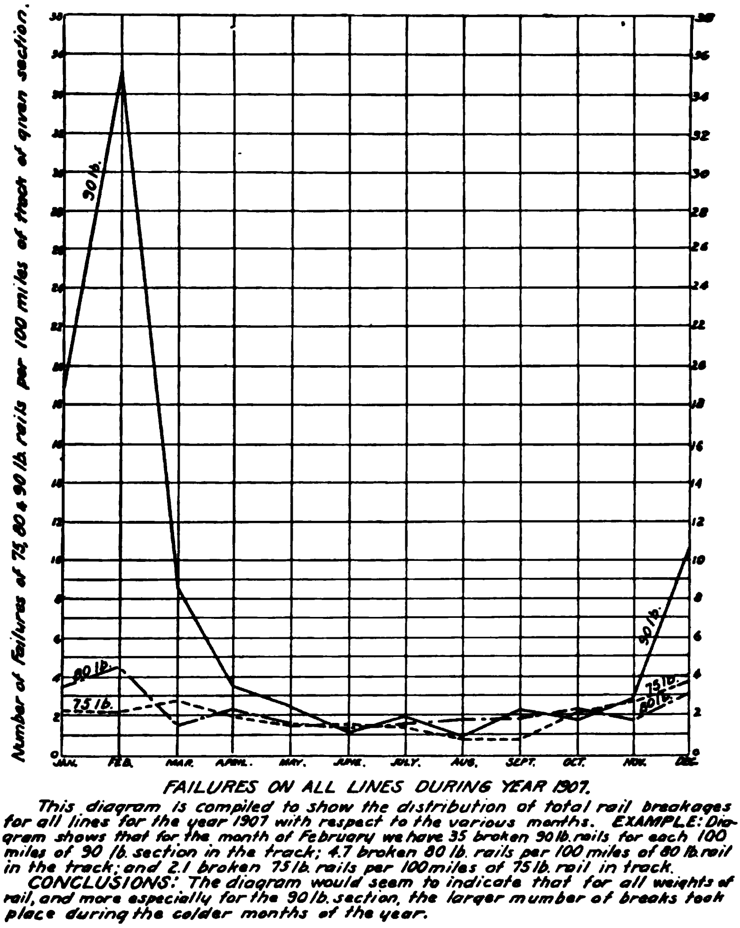
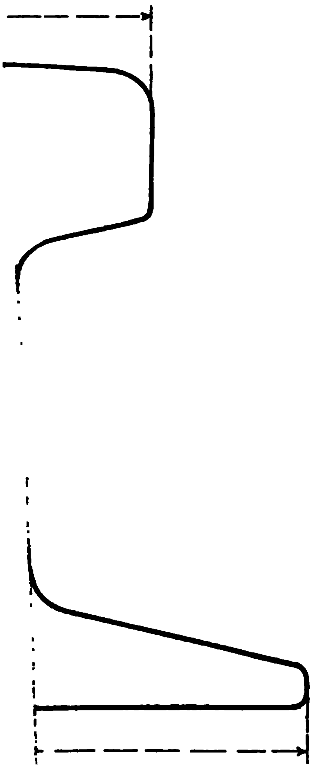
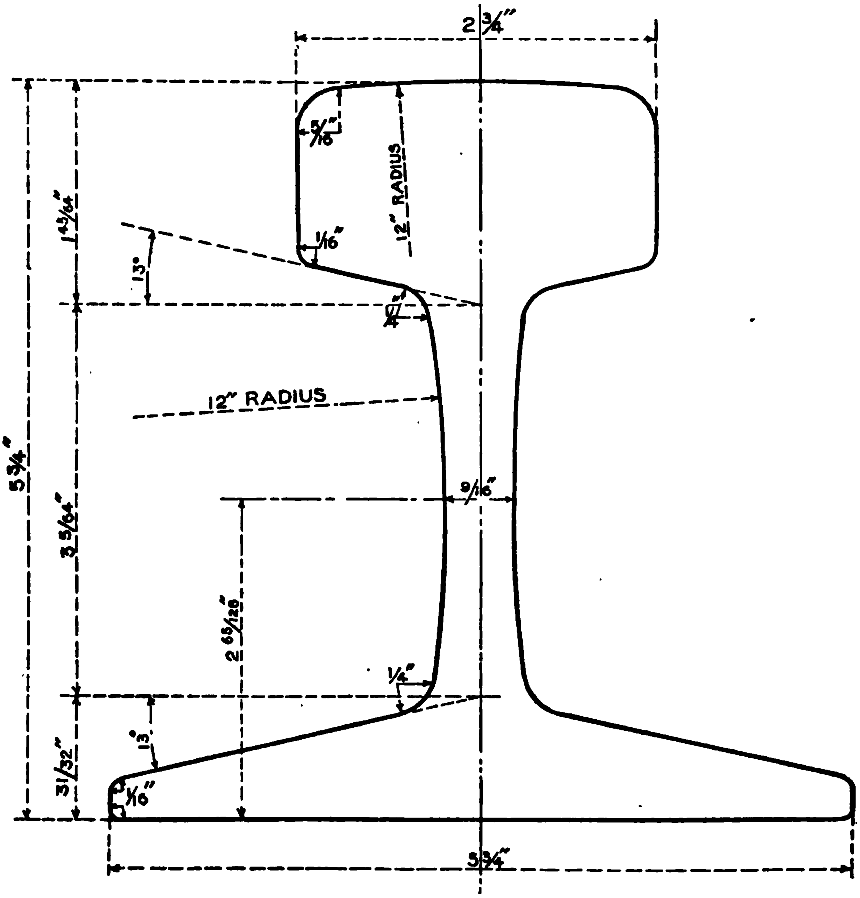


Fig. 361. — Diagram of Rail Failures, Harriman Lines. (Am. Ry. Eng. Assn.)





100 lbs. per yd.

of Head to Area of Head 1.87
" Web " " " Web 3.73
" Base " " " Base 3.32

phery to Total Area 2.78
25
, 10.30
, 11.97

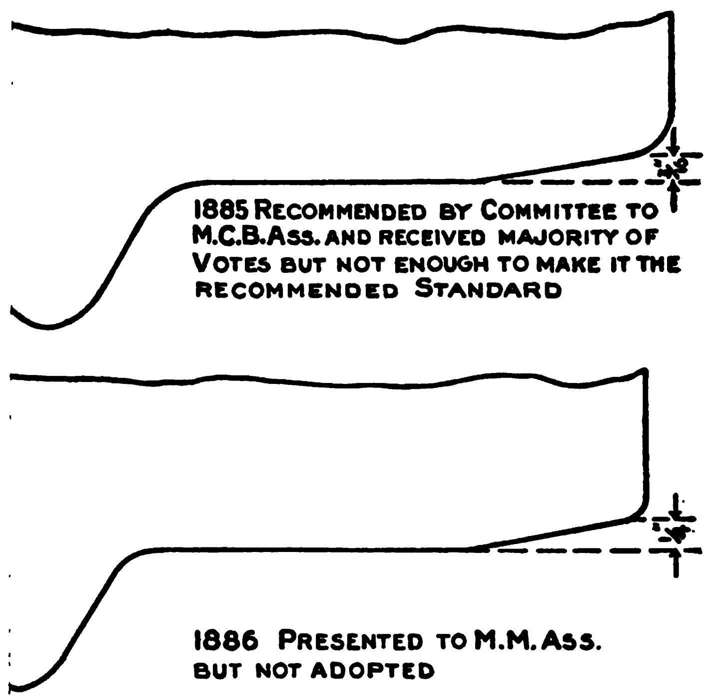
erican Society of Civil Engineers (adopted 1893).

Area of Head	4.13 sq. in.	42%	
" " Web	2.06 " "	21%	
" " Base	3.63 " "	37%	
Total	9.82 sq. in.	100%	

Ratio Periphery of Head to Area of Head 1.66
" " " Web " " " Web 3.43
" " " Base " " " Base 3.06

Ratio Total Periphery to Total Area 2.55

Moment of Inertia, 43.8
Section Modulus, Head, 14.44
Section Modulus, Base, 16.11



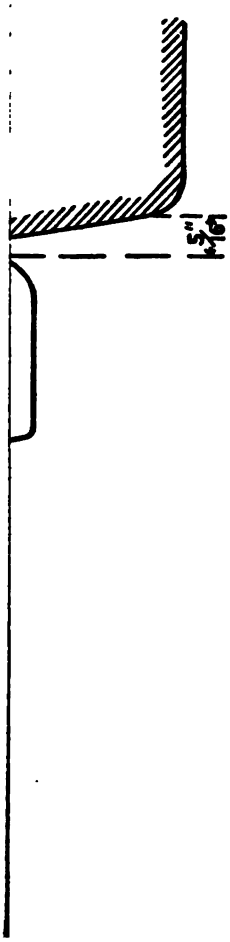
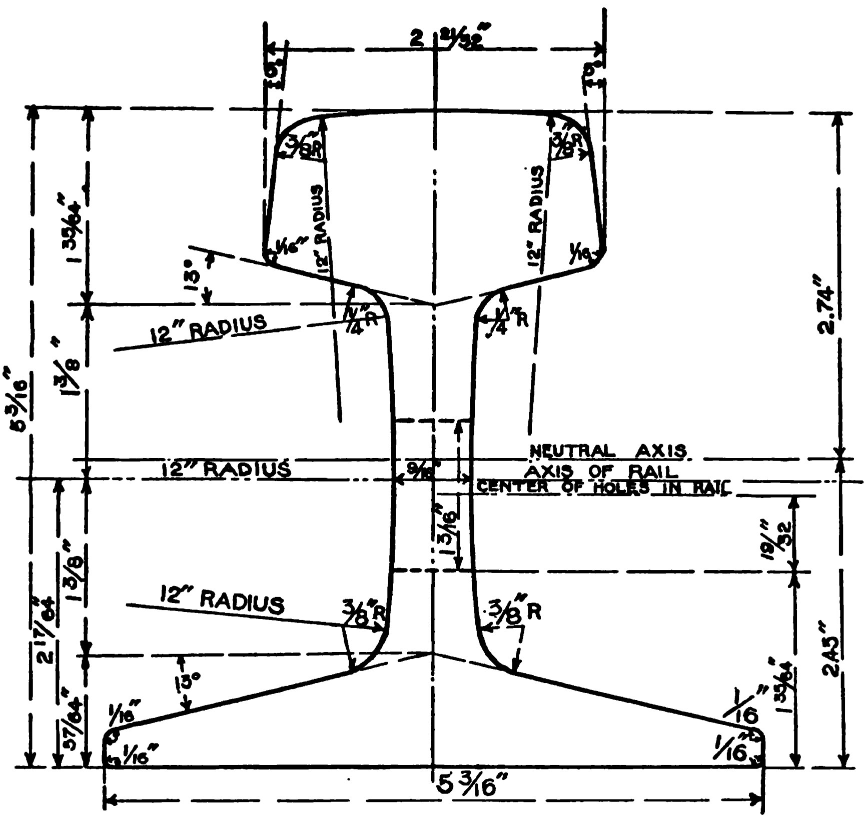
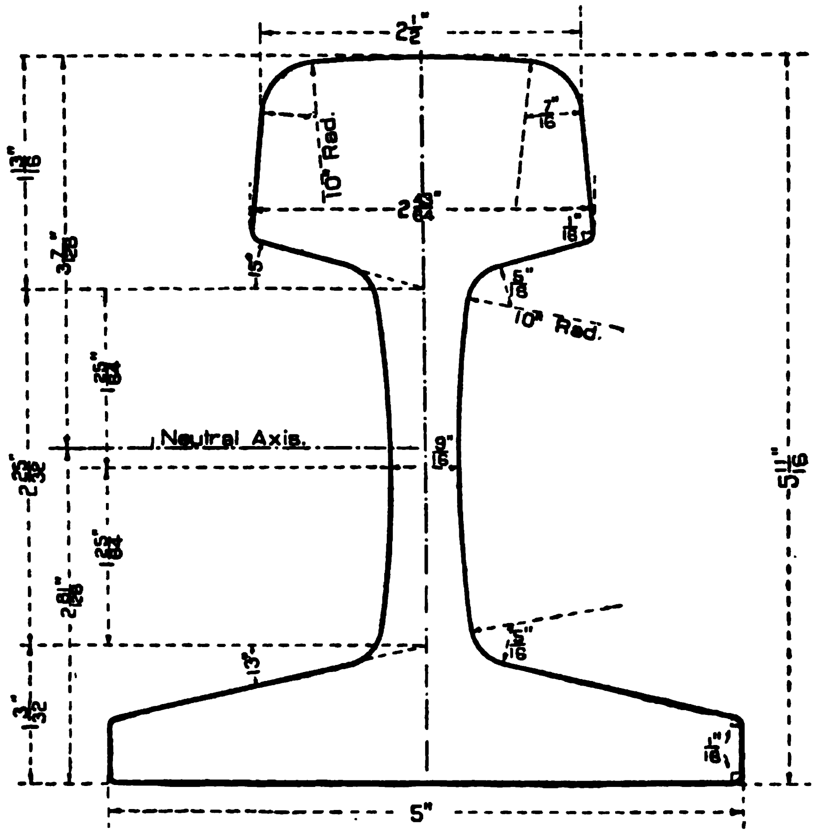


PLATE III.

Standard Wheel Sections showing Coning of Wheel.



85 lbs. per yd.
Chicago, Burlington and Quincy Railroad.

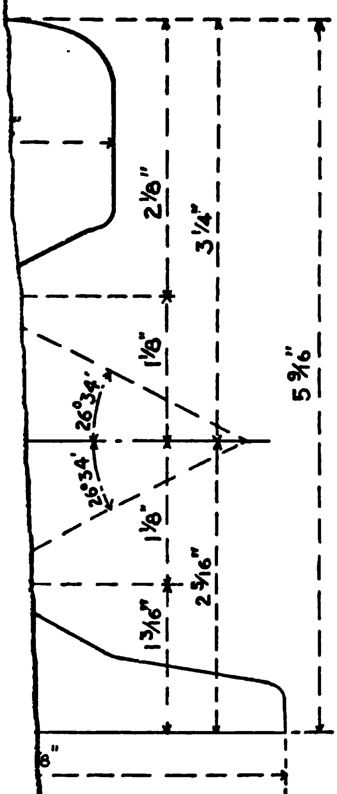


100 lbs. per yd.

Area of Head	4.09 sq. in.	41%	Ratio Periphery of Head to Area of Head	1.59
" " Web	1.85 " "	19%	" " " Web " " " Web	3.58
" " Base	4.03 " "	40%	" " " Base " " " Base	2.43
Total	9.97 sq. in.	100%	Ratio Total Periphery to Total Area	2.30

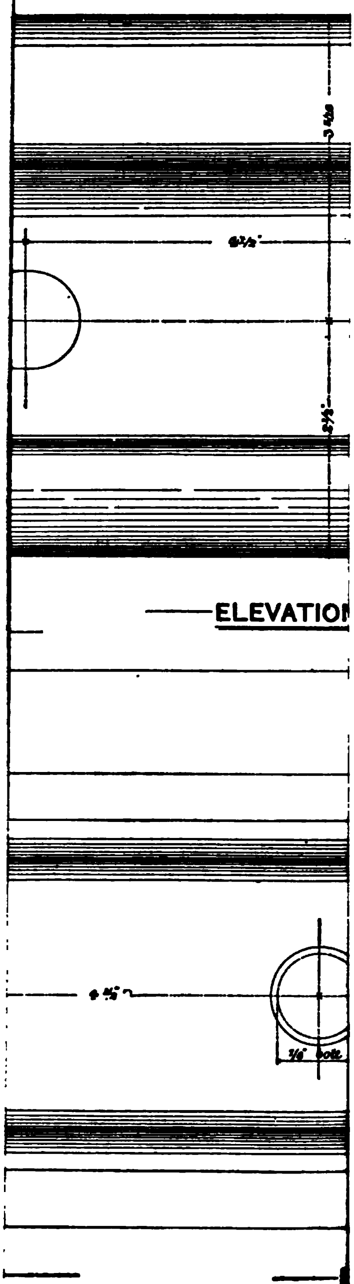
Moment of Inertia, 41.9
Section Modulus, Head, 13.71
Section Modulus, Base, 15.91

Pennsylvania Railroad System (adopted 1907).

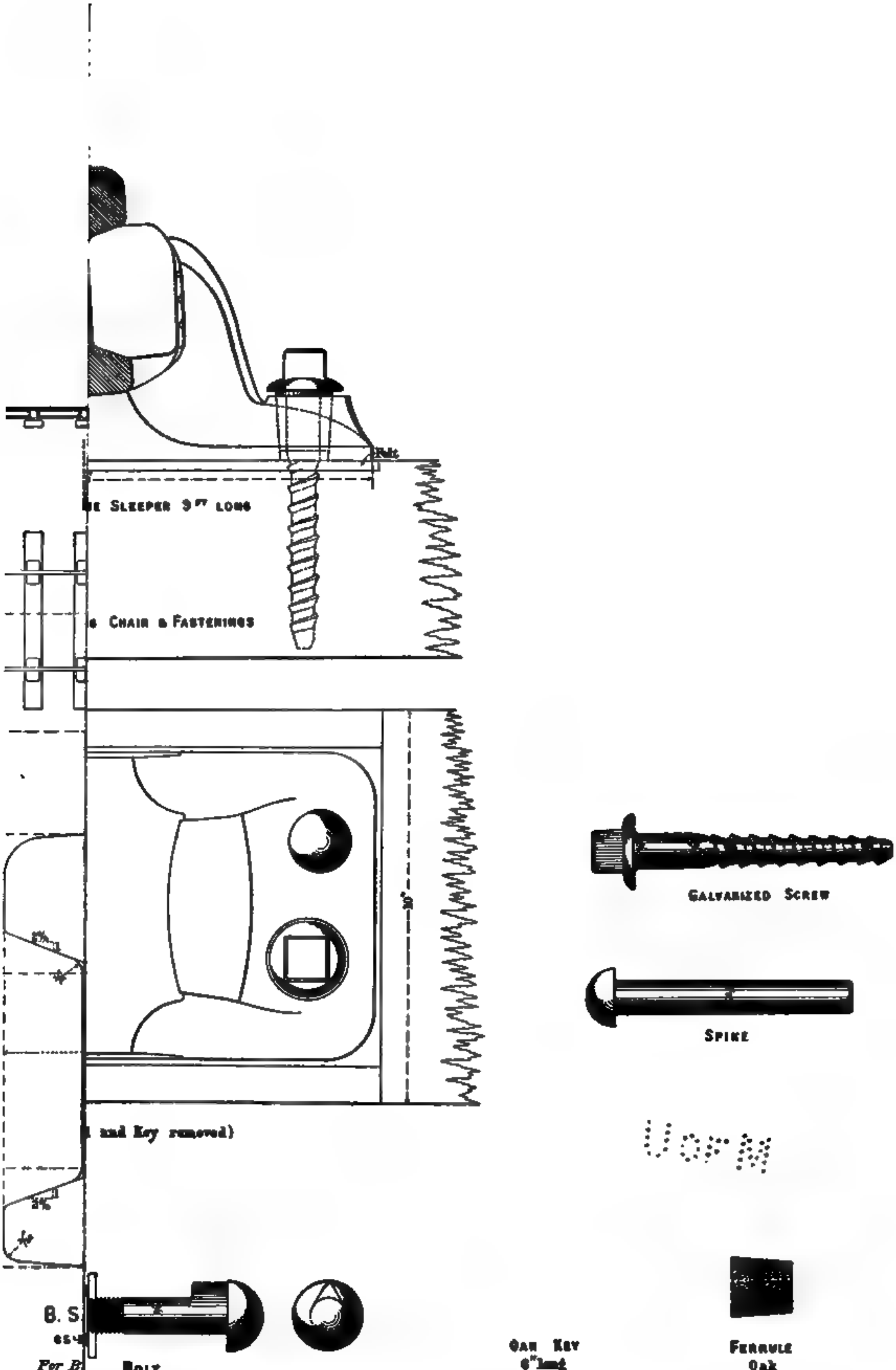


yd.
Railway.

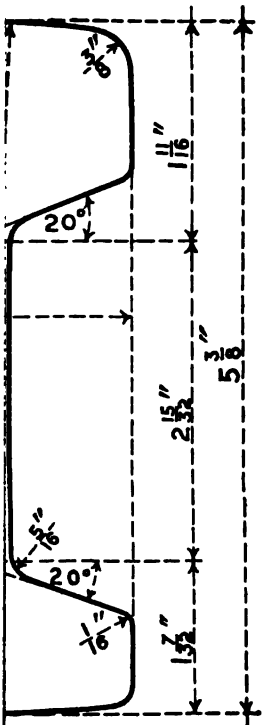
Plate X.—Rail Sections



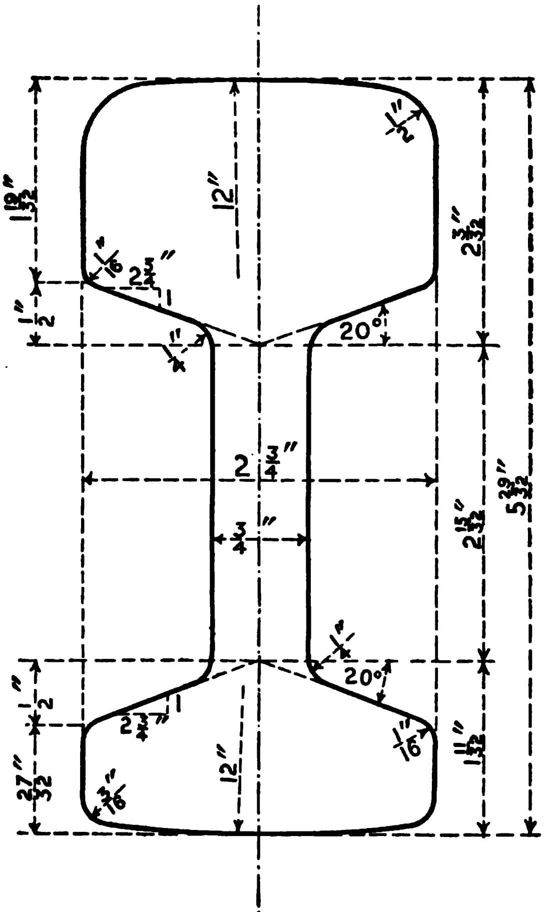
Railway, Permanent Way, 1907.



I.—L. & | weigh 54 lbs. each. The ordinary or intermediate chairs are 7¾ ins. wide, and weigh 45 lbs. each.

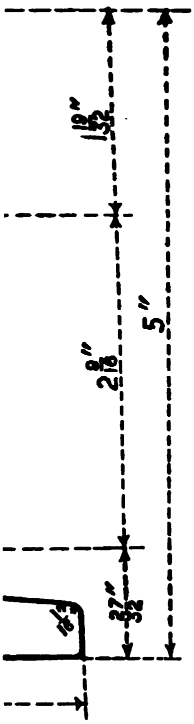


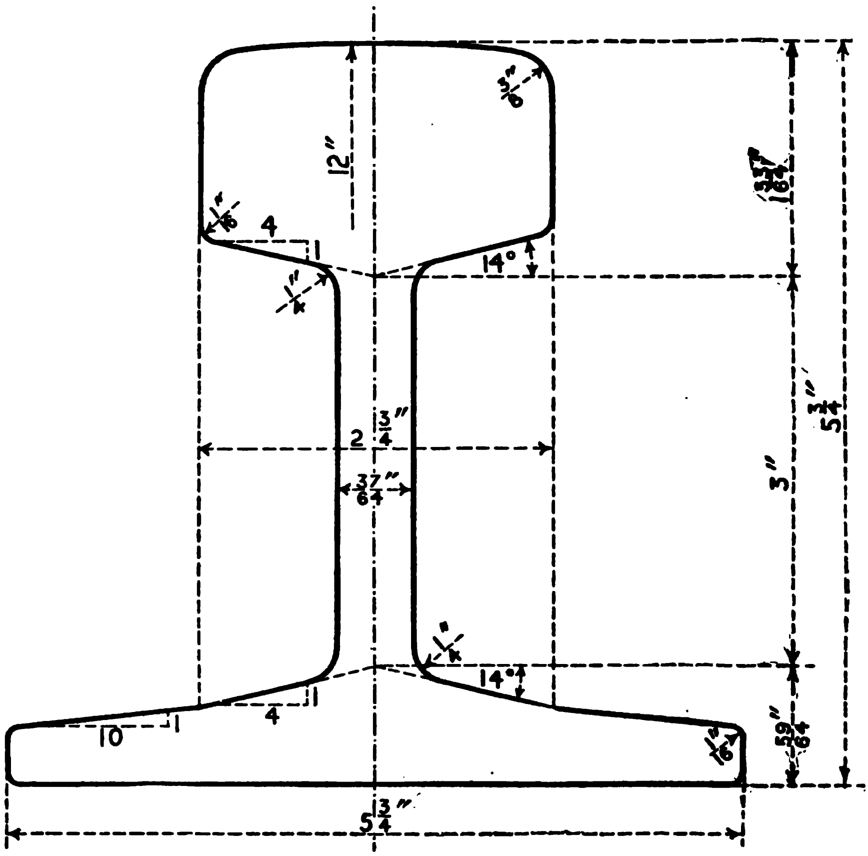
yd.
No. 80.



100 lbs. per yd.
"B. S." Section No. 100.

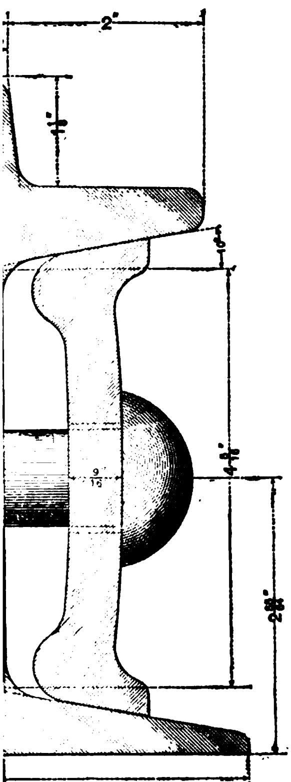
Bull Head Railway Rails.





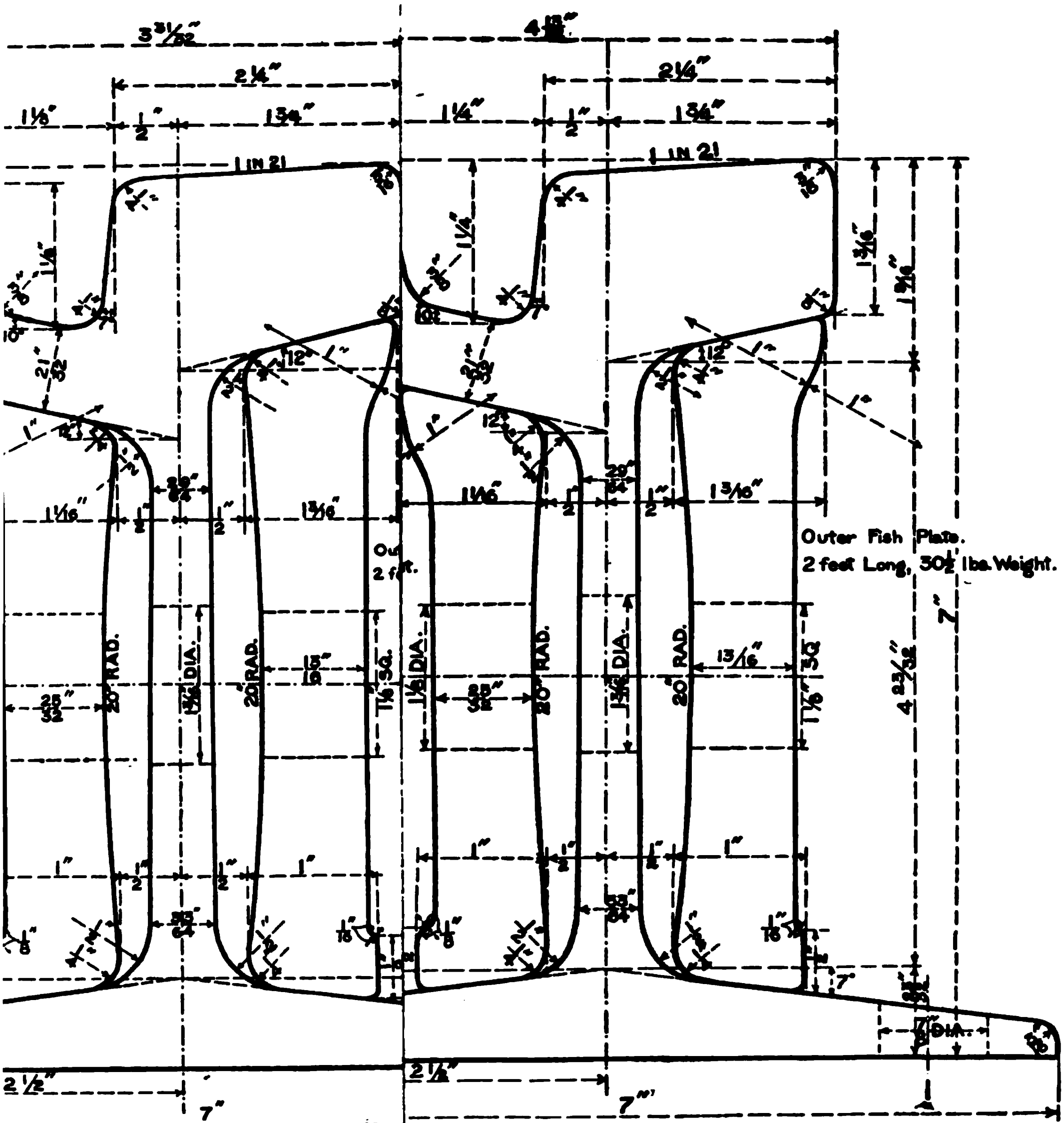
100 lbs. per yd.
"B. S." Section No. 100.

Bottom Railway Rails.



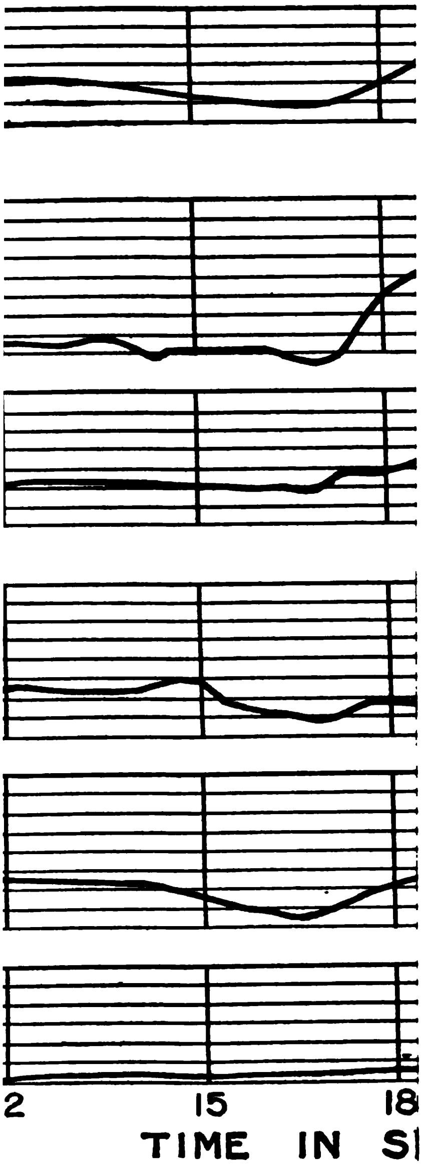
r yd.

I. — Rail Sections for Street Rail

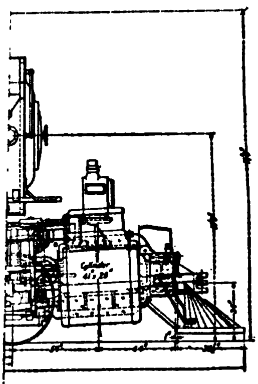


110 lbs. per yd.
"B.S." Section No. 5.

116 lbs. per yd.
"B.S." Section No. 5c.
For use on curves.



f Driving Wheel Spring, Consolidation En



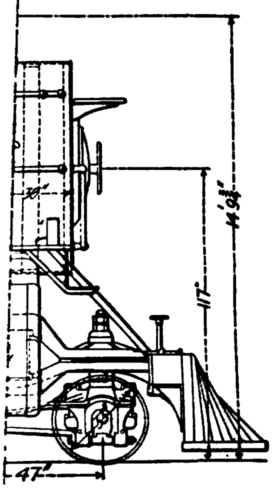


Plate XXI.—Freight Locomo

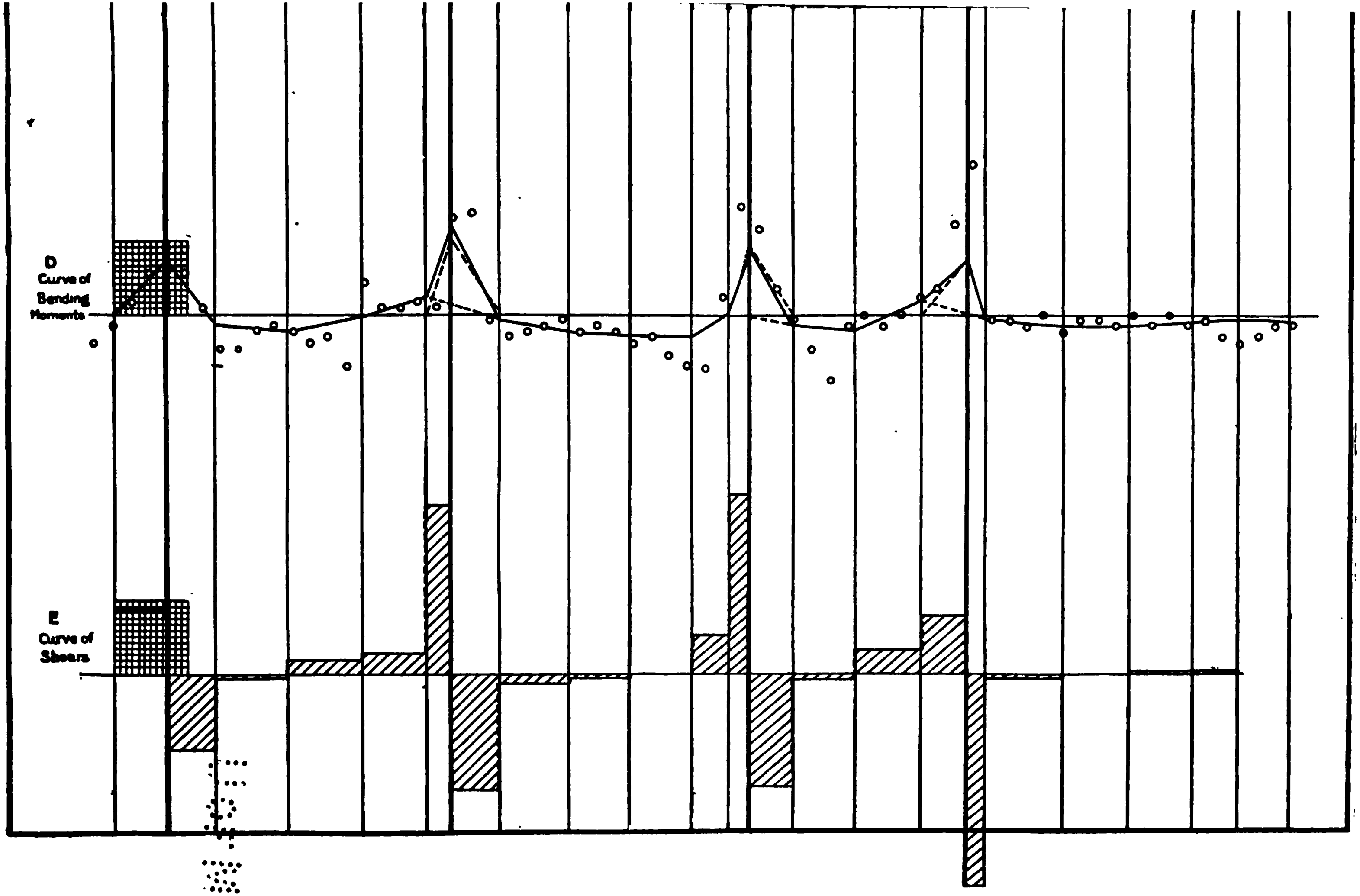


PLATE XXIII. — Rail Diagram of Love. 0.46 original size.

Note. — In the curve of bending moments, the maximum bending moments under the wheels are determined by combining the normal moment diagrams, shown in dotted lines, with the moments at the adjacent ties.

Joint.			
...rbon.	Manganese.	Elastic Limit.	Ultimate Strength.
%	%	lbs. per sq. in.	lbs. per sq. in.

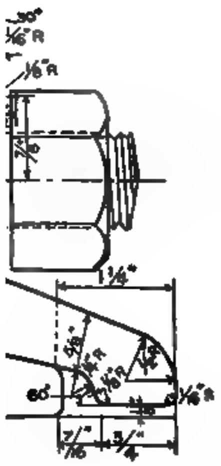
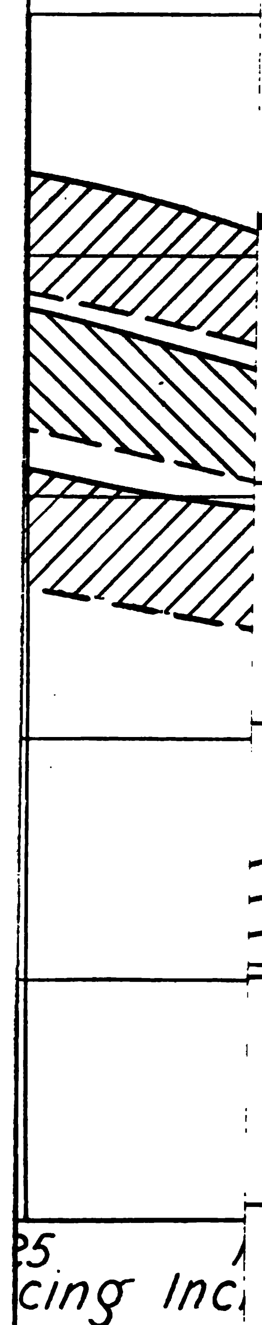
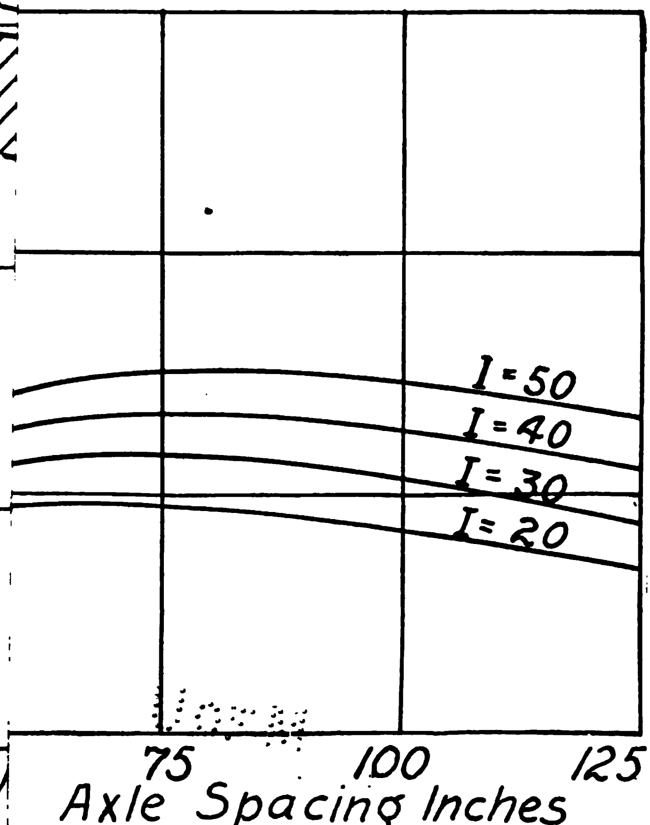


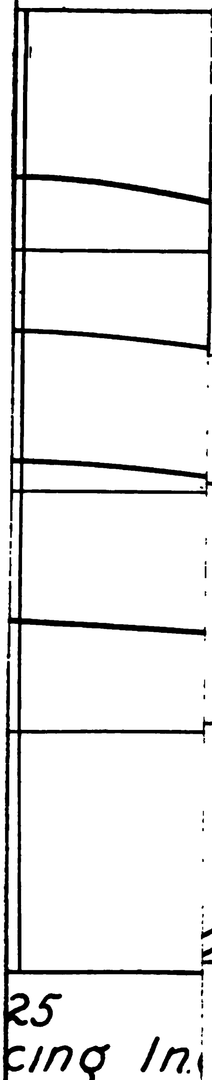
Fig. F. 30 inc



I.—Dynamic Wheel Loads for Various Rails and Axle Spacing.

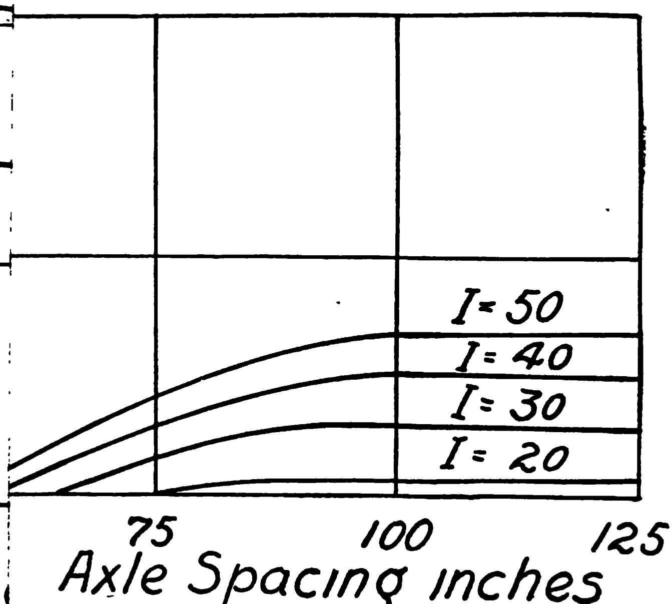


Class C Track.



DING MOMENTS IN DIFFERENT RAILS WHICH WILL CAUSE AN EXTREME FIBER STRESS OF 0,000 LBS. PER SQ. IN. IN THE BASE OF THE RAIL.

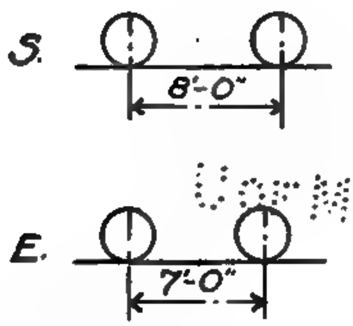
I	Section Modulus of Base (assumed).	Bending Moment, inch pounds.
50	18.0	360,000
45	16.5	330,000
40	15.0	300,000
35	13.5	270,000
30	12.0	240,000
25	10.5	210,000
20	9.0	180,000



Class C Track.

PLAT

,oading and Classes of Track.



rurban Cars on Electric Roads.

Average Analysis of Heats Accepted.
...fter column 45, Sulphur, add 2 columns
...thout headings to be numbered 46 & 47.

...d. Average Analysis of Heats Rejected
...fter column 52, Sulphur, add 2 columns
...ithout headings to be numbered 53 & 54

3rd. Change the numbers of columns as shown.

	Average Analysis of Heats Rejected					% of Ingot Discarded		Permanent deflection under Drop Test	Shrinkage allowed in inches	Effect of Retest (a)		No. of Heats showing Rails with interior defect		Lines
...lphur	Carbon	Mang.	Phos.	Sil.	Sulphur	From Top	From Bottom			Tons Accepted	Heats Accepted	No. of Heats	% of Total	
45	48	49	50	51	52	55	56	57	58	59	60	61	62	
														1
														2
														3
														4
														5
														6
														7
														8
														9
														10
														11
														12
														13
														14
														15
														16

...STS AND INSPECTION.

...teel. If
...ll be tested
...ical defect,
...of the test
...epted as No. 1
...is less or

...shows
...hat heat

...pieces
...second rails

of the same heat. If two out of three of these second test pieces break, the remainder of the rails of the heat will also be rejected. If two out of three of these second test pieces do not break, the remainder of the rails of the heat will be accepted, provided they conform to the other requirements of these specifications, as No. 1 or No. 2 classification, according as the deflection is less or more, respectively, than the prescribed limit."

(d.) If any test piece, test "a", does not break, but when nicked and tested to destruction shows interior defect, the top rails from each ingot of that heat shall be rejected."

INDEX